Review on Wellhead Uplift Phenomenon in Offshore Thermal Recovery Wells

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Abstract

With the continuous rise in global energy demand and the gradual depletion of onshore conventional oil and gas resources, the development of offshore heavy oil resources has become a key strategic direction for the petroleum industry. Heavy oil reserves account for a relatively high proportion of total oil reserves in China's Bohai Sea area. This type of resource is characterized by high viscosity and poor fluidity, resulting in extremely low recovery rates with conventional mining technologies. Therefore, cyclic steam stimulation (CSS) is widely used as the mainstream thermal recovery technology. This technology heats the formation by periodically injecting high-temperature steam to reduce the viscosity of heavy oil, thereby achieving efficient recovery. However, during this process, the wellbore is subjected to severe thermal cycling, causing significant thermal expansion of the casing string due to high temperatures, which in turn triggers wellhead uplift. Field data show that the wellhead uplift of some offshore thermal recovery wells has reached a relatively high level, which not only threatens the integrity of wellhead seals, subsea connections, and riser systems but also poses a serious hazard to the overall safety of the platform. It may even lead to production interruption and huge economic losses. Therefore, in-depth research on the relevant mechanisms, prediction methods, and prevention and control measures of wellhead uplift in offshore thermal recovery wells is of great engineering significance and practical value for ensuring the safe and efficient development of offshore heavy oil.

Keywords

Offshore Thermal Recovery Well; Wellhead Uplift; Prediction Model; Casing Thermal Expansion; Cement Sheath Friction; Finite Element Analysis.

1. Core Mechanisms and Multi-Field Coupling Characteristics of Wellhead Uplift

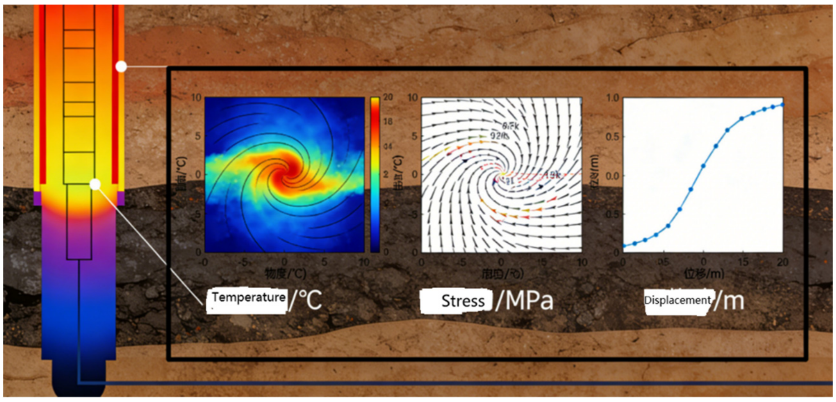

Fig 1. multi field coupling mechanism

Wellhead uplift in offshore thermal recovery wells is not caused by a single factor but is a complex nonlinear phenomenon under the coupling of thermal, mechanical, and other fields.

Its formation and evolution involve multiple key links, such as uneven thermal expansion, trapped annular pressure, dynamic evolution of cement sheath debonding, and marine environment modulation. These factors interact with each other and jointly determine the degree and development trend of wellhead uplift.

1.1. Uneven Thermal Expansion: The Dominant Driving Force for Wellhead Uplift

During steam injection, high-temperature steam flows down the wellbore, transferring a large amount of thermal energy to the casing, cement sheath, and surrounding formation. According to the theory of linear thermal expansion, the elongation of the casing is positively correlated with the coefficient of thermal expansion, heated length, and temperature rise. There are differences in the coefficient of thermal expansion among different casing materials, and this material difference directly affects the degree of thermal expansion of the casing.

However, the actual wellbore temperature field exhibits significant unevenness, mainly due to different heat transfer mechanisms along the well depth. The upper air and seawater sections heat up rapidly due to strong convective heat loss, and the convective heat transfer coefficient of seawater is much higher than that of formation rocks, resulting in a rapid temperature rise of the casing in this section in a short time. In contrast, the deep formation heats up slowly through thermal conduction and is subject to mechanical constraints from overlying rock stress, leading to a limited temperature rise. The upper well section can be regarded as the "active expansion zone," while the deep well section, due to small temperature changes and strong formation constraints, hardly produces obvious expansion and becomes the "anchored zone." This uneven expansion between the upper and lower well sections causes complex redistribution of axial stress in the multi-layer casing string. The expansion of the upper casing is restricted by the lower anchored zone, thereby generating an upward thrust that drives the wellhead to lift. The thermal load caused by high temperature will also damage the cementing quality of the first interface of cementing, causing some casings to break away from the constraint of the cement sheath and become free casings, further increasing the upward thrust. This process has been verified many times in the actual production of thermal recovery wells in multiple offshore oilfields such as the Bohai Sea and the South China Sea[3].

1.2. Trapped Annular Pressure: An Important Auxiliary Factor for Wellhead Uplift

In addition to thermal effects, annular pressure plays an important auxiliary role in wellhead uplift. The wellbore structure of offshore thermal recovery wells usually includes multiple layers of casing, forming annular spaces between the casings. These annular spaces may contain residual drilling fluid, cement slurry filtrate, formation fluids, and other media. When the annulus is sealed by packers or closed valves, the annular fluid expands when heated under the high temperature brought by steam injection, and the sealed state restricts the volume expansion of the fluid, thereby generating "trapped pressure" (i.e., annular pressure buildup, APB)[1]. This pressure acts on the bottom and top of the casing through the end cap effect, exerting an upward axial force on the casing and driving the wellhead to displace upward[5].

In offshore heavy oil thermal recovery wells, the large temperature difference between low-temperature seawater and high-temperature heavy oil makes the temperature of the annular fluid prone to drastic changes during operation, further exacerbating the pressure buildup[1]. The magnitude of annular pressure is closely related to factors such as the type of annular fluid, temperature change range, annular sealing degree, and annular volume. For example, if the annular fluid is water, its volume expansion coefficient is relatively large, resulting in higher trapped pressure under the same temperature change. Moreover, the tighter the annular seal, the more difficult it is for the fluid to leak, and the more significant the pressure buildup effect.

It is worth noting that the influence of annular pressure is not independent but forms a dynamic coupling relationship with the thermal field. The higher the steam injection rate, the faster the wellbore temperature rises, and the more rapid the expansion of the annular fluid. At the same time, a higher steam injection rate also means that the annular seal may be better, and the pressure buildup rate accelerates accordingly, thereby further amplifying the wellhead uplift effect and synergistically aggravating the wellhead displacement with thermal expansion[1]. Severe annular pressure buildup will not only exacerbate wellhead uplift but also may lead to casing yield deformation, cement sheath rupture, and other problems, and even cause wellbore integrity damage, resulting in significant economic losses and safety risks[5].

1.3. Dynamic Evolution of Cement Sheath Debonding: A Key Transformation of Constraint Mechanism

As a connecting medium between the casing and the formation, the cement sheath mainly functions to fix the casing, isolate formation fluids, protect the casing from formation corrosion, and restrict the expansion of the casing. In the initial state, the cement sheath forms a strong mechanical constraint through interfacial bonding with the outer wall of the casing and the formation rock, which can effectively limit the axial expansion and radial deformation of the casing. The interfacial bonding strength between the cement sheath and the casing is affected by factors such as cement slurry formulation, cementing construction quality, and formation conditions.

However, during the periodic steam injection of offshore thermal recovery wells, the casing undergoes repeated heating-cooling cycles, resulting in alternating thermal stresses between the casing and the cement sheath[2]. During the heating phase, the casing expands when heated, but the coefficient of thermal expansion of the cement sheath is different from that of the casing. The expansion of the casing is restricted by the cement sheath, generating tensile stress at the casing-cement sheath interface. During the cooling phase, the casing contracts, generating compressive stress at the interface[4]. The long-term thermal cycling causes the repeated accumulation of tensile stress at the casing-cement sheath interface. When the local tensile stress exceeds the cement bonding strength, microcracks will appear at the interface. With the increase in the number of thermal cycles, the microcracks continue to expand, eventually leading to debonding between the casing and the cement sheath[2].

Debonding usually starts near the wellhead where the thermal strain is the largest, because the temperature change of the casing near the wellhead is the most drastic, and the thermal stress concentration is the highest[4]. Subsequently, the debonded area gradually expands downward with each steam cycle, and this failure process is progressive and irreversible[2]. After debonding occurs, the constraint mechanism of the cement sheath on the casing changes from bonding constraint to frictional resistance constraint based on contact pressure and friction coefficient[4]. The magnitude of frictional resistance is related to contact pressure and friction coefficient. The contact pressure mainly comes from the radial shrinkage of the cement sheath and formation pressure, while the friction coefficient is related to factors such as casing surface roughness, cement sheath surface state, and annular medium. Although frictional resistance is weaker than bonding constraint, it can still partially alleviate the free expansion of the casing and play a certain role in inhibiting wellhead uplift. This transformation of the constraint mechanism causes a sudden change in the expansion resistance of the casing, which is a key inflection point for the nonlinear evolution of wellhead displacement[4]. Analysis of cement sheath integrity under multi-load coupling conditions shows that thermal load is the core inducement leading to interface debonding and weakening the constraint effect, while factors such as annular pressure and formation stress will accelerate the development of the debonding process[3].

1.4. Modulation Effect of Marine Environment: A Unique Risk Amplification Factor

The special marine environment adds unique complexity to the problem of wellhead uplift. Compared with onshore thermal recovery wells, offshore thermal recovery wells have higher wellhead uplift risks and more complex influencing factors, which are mainly derived from the modulation effect of the particularity of the marine environment on wellhead uplift.

Firstly, the space of offshore platforms is limited, and various equipment are compactly arranged. The wellhead device is closely connected with other structures and pipelines of the platform, which strictly restricts the allowable displacement of the wellhead. Under normal circumstances, the allowable uplift of offshore platform wellheads is much lower than that of onshore wells, making offshore thermal recovery wells extremely sensitive to slight uplift. Even a small amount of uplift may lead to excessive stress on the wellhead connection parts and seal failure[3].

Secondly, the thermal boundary condition of the seawater section is highly dynamic. The flow of ocean currents continuously takes away the heat of the wellbore, making the temperature distribution of the casing in the seawater section show dynamic changes. At the same time, the seawater temperature itself is low and has seasonal fluctuations, forming a strong thermal contrast with high-temperature steam, resulting in a much larger temperature gradient of the casing in the seawater section than that of the corresponding well section of onshore wells[5]. This dynamic and drastic temperature change makes the thermal expansion and contraction of the casing in the seawater section more frequent, further exacerbating the fatigue damage of the casing and the cumulative effect of wellhead uplift[1]. In addition, seawater is highly corrosive, which will affect the surface properties of the casing and cement sheath, possibly reducing the bonding strength and friction coefficient of the casing-cement sheath interface and indirectly affecting the development of wellhead uplift[2].

Furthermore, some offshore developments adopt subsea wellhead structures. Compared with onshore wellheads and offshore platform wellheads, the heat transfer path of subsea wellheads is more complex, affected by factors such as seawater temperature, ocean currents, and thermal conductivity of seabed sediments. At the same time, the mechanical boundary conditions of subsea wellheads have also changed, and the fixing method and constraint state of the casing are different from other types of wellheads[5]. In addition, the pressure relief operation in the marine environment is more complex. Once annular pressure builds up, the pressure relief of subsea wellheads is more difficult and costly, further increasing the difficulty of risk management and control[1]. These factors collectively increase the risk level of offshore thermal recovery wells, requiring prediction models and prevention and control measures to fully consider the particularity of the marine environment[3].

2. Technical Framework and Development Trend of Wellhead Uplift Prediction

Wellhead uplift prediction is the premise and foundation for risk management and control. Accurate prediction can provide a scientific basis for engineering design, production optimization, and the formulation of prevention and control measures. With the deepening understanding of the mechanism of wellhead uplift, prediction technology has also experienced a development process from simplicity to complexity and from empirical to mechanistic, gradually forming a technical framework integrating multiple methods.

2.1. Limitations of Traditional Prediction Methods

Early wellhead uplift prediction methods were mainly based on simplified assumptions, focusing on empirical formulas and simple theoretical analyses. Among them, the most representative is the prediction method based on the assumption of free thermal expansion of the casing, which holds that the casing can expand freely axially under thermal action without being constrained by the cement sheath, formation, etc., and the wellhead uplift is equal to the free thermal expansion of the casing.

However, offshore wells mostly adopt full-well cementing design, and the constraint effect of the cement sheath and formation on the casing cannot be ignored. This assumption is fundamentally contradictory to the actual engineering conditions[3]. In actual working conditions, the expansion of the casing is subject to the bonding constraint and frictional constraint of the cement sheath as well as the mechanical constraint of the formation. Free expansion almost does not exist, leading to the prediction results of traditional methods often being much larger than the actual measured values with large errors, which are difficult to meet the engineering accuracy requirements[1].

Although some recent studies have begun to incorporate cement sheath friction into prediction models and correct the free expansion by introducing friction resistance coefficients, existing models still have obvious shortcomings[4]. On the one hand, most of these models ignore the mechanical coupling effect between multi-layer casing strings and analyze each layer of casing as an independent individual. In reality, multi-layer casings interact through the cement sheath or annular fluid, and the expansion of one layer of casing will be constrained by other casings. This coupling effect will significantly affect the overall wellhead uplift[5]. On the other hand, the models do not fully characterize the uneven thermal field along the wellbore, usually simplifying the temperature distribution by using average temperature or segmented constant temperature, which cannot accurately reflect the dynamic evolution of the temperature field and the impact of spatial differences on casing expansion[1]. In addition, existing models do not consider the dynamic evolution of cement sheath debonding under cyclic thermal loads and assume that the constraint state remains unchanged, which is inconsistent with the actual situation where the constraint mechanism changes dynamically with the number of thermal cycles, making it difficult to further improve the prediction accuracy[2].

2.2. Construction and Improvement of Multi-Field Coupling Prediction Models

To make up for the defects of traditional methods, scholars have developed a multi-field coupling wellhead uplift prediction model based on thermodynamics principles, elastic mechanics theory, and casing-cement sheath interaction mechanism[3]. This model breaks through the limitations of traditional assumptions, integrates key factors such as thermal expansion, trapped annular pressure, and progressive debonding of the cement sheath-casing interface into a unified analytical framework, and achieves accurate prediction of wellhead uplift through a segmented calculation scheme along the depth direction[4].

The core logic of the multi-field coupling prediction model is to simulate the evolution laws of the temperature field, stress field, and displacement field of the wellbore during thermal cycling and the interaction between various physical fields through numerical calculation methods[1]. The construction of the model usually follows the following steps: first, establish a three-dimensional geometric model of the wellbore, clarify the structural parameters and material properties of the casing, cement sheath, and formation; second, determine the boundary conditions, including thermal and mechanical boundary conditions such as steam injection temperature, pressure, and flow rate, as well as constraint conditions related to the marine environment[3]; third, solve the wellbore temperature field based on the heat conduction equation to obtain the temperature distribution at different times and depths[1]; fourth, calculate the thermal stress of the casing and cement sheath according to the temperature field, and combined with the stress generated by annular pressure, analyze the stress state of the casing-cement sheath interface to determine whether debonding occurs[2]; finally, calculate the axial displacement of the casing according to the constraint state (bonding or friction) and accumulate to obtain the wellhead uplift[4].

Existing studies have formed a relatively complete system of mechanism analysis methods by establishing a three-dimensional wellbore temperature field model and a complex multi-string wellhead uplift theoretical calculation model[3]. For example, some models use the finite difference method to solve the temperature field, which can accurately capture the dynamic changes of temperature along the well depth and time; in stress calculation, the mutual constraint of multi-layer casings and the end cap effect of annular pressure are considered[5]; in the judgment of interface debonding, the maximum tensile stress criterion is adopted, combined with the cement sheath bonding strength, to dynamically simulate the expansion process of the debonded area[4]. The core advantage of the model is that it can dynamically switch between bonding constraint and frictional constraint modes according to the local stress state, truly reflecting the progressive characteristics of wellhead uplift under actual working conditions[2]. Compared with traditional models, the prediction accuracy of the multi-field coupling prediction model has been significantly improved, which can meet the actual engineering needs[1].

2.3. Establishment of Multi-Method Verification System

To ensure the theoretical rigor and engineering applicability of the prediction model, a multi-dimensional verification system of "analytical modeling - numerical simulation - physical experiment - field verification" has been established in the research. Through the mutual complementarity and confirmation of different methods, the reliability and credibility of the model are improved[3].

Analytical modeling is the theoretical basis of the prediction model. By abstracting and simplifying the physical process of wellhead uplift, establishing and solving mathematical equations, it can clearly reveal the intrinsic relationship between various factors and wellhead uplift[1]. The analytical model has the advantages of high calculation efficiency and clear physical meaning, and can be used to quickly analyze the sensitivity and influence laws of key parameters. However, due to the existence of simplified assumptions, its application scope and prediction accuracy are subject to certain limitations[5].

As an important supplement to analytical modeling, numerical simulation can handle complex geometric structures, boundary conditions, and physical field coupling problems[4]. Commonly used numerical simulation software includes ABAQUS, ANSYS, etc. By establishing a three-dimensional refined model, it can intuitively reproduce the stress redistribution, cement sheath debonding expansion, casing deformation, and other processes[2]. Numerical simulation can simulate wellhead uplift under different working conditions, such as different steam injection parameters, different casing structures, and different cement sheath properties, providing strong support for model parameter optimization and mechanism analysis[3]. For example, through numerical simulation, it can be found that the debonding of the casing-cement sheath interface first occurs near the wellhead and gradually expands downward with the increase in the number of thermal cycles, which is consistent with the results of physical experiments and field observations[4].

Physical experiment is an important means to verify model assumptions and mechanisms[2]. By building a scaled or full-scale experimental device to simulate the wellbore structure and steam injection conditions of offshore thermal recovery wells, parameters such as wellhead uplift, casing stress, and annular pressure can be directly measured, and the influence laws of various factors on wellhead uplift can be quantified[4]. In physical experiments, three-layer concentric steel pipes are usually used to simulate the multi-layer casing system, heating devices are used to simulate the high-temperature environment of steam injection, and pressure sensors, displacement sensors, and other equipment are used to collect data[2].

Experimental results show that the annular sealing state has a significant impact on the wellhead uplift, and the wellhead uplift of the sealed annulus is significantly larger than that of the open annulus. At the same time, the higher the bonding strength of the cement sheath, the stronger the constraint effect on the casing, and the smaller the wellhead uplift[1]. These experimental results not only verify the core model assumptions but also provide measured data for model parameter calibration[3].

Field verification is the final link to test the engineering applicability of the model[5]. By selecting typical offshore thermal recovery wells, collecting on-site steam injection parameters, wellbore structure parameters, temperature and pressure monitoring data, and actual wellhead uplift data, the model prediction results are compared and analyzed with the on-site data to calibrate the model parameters and optimize the model structure[1]. This multi-method collaborative verification model provides strong support for the reliability of the model. For example, the application effect of prevention and control measures is effectively verified by combining the annular pressure buildup prediction model with on-site case simulation[5].

2.4. Development Trend of Prediction Technology

In the future, the wellhead uplift prediction technology for offshore thermal recovery wells will develop in the direction of refinement, intelligence, and integration[3]. In terms of model refinement, the multi-physics coupling model will be further improved to fully consider the temperature dependence and time-dependent evolution of material properties, such as the elastic modulus of the casing and the bonding strength of the cement sheath will decay over time at high temperatures[4]. At the same time, the dynamic characteristics of the marine environment will be more accurately described, such as the impact of ocean currents on the temperature field and the effect of seawater corrosion on interface performance, so as to improve the adaptability of the model to complex working conditions[2].

In terms of intelligence, technologies such as machine learning and big data analysis will be integrated to establish a hybrid prediction model combining data-driven and mechanism-based modeling[1]. By collecting a large amount of on-site data, experimental data, and numerical simulation data, training machine learning models to mine potential laws and correlations in the data, and making up for the shortcomings of mechanism-based models in dealing with complex nonlinear problems and uncertain factors[5]. For example, using neural network models to predict the attenuation law of cement sheath bonding strength, or predicting wellhead uplift under different working conditions based on historical data, so as to improve prediction efficiency and accuracy[4]. At the same time, combined with real-time monitoring data, the online update and dynamic correction of the prediction model will be realized to improve the timeliness and accuracy of prediction[2].

In terms of integration, a comprehensive decision-making system integrating wellhead uplift prediction, risk assessment, and optimization of prevention and control measures will be constructed[3]. The system will integrate prediction models, risk evaluation indicators, prevention and control measures databases, etc., automatically evaluate the wellhead uplift risk level according to the prediction results, and recommend the optimal prevention and control plan to realize the closed-loop management from prediction to prevention and control[1]. In addition, prediction technology will be deeply integrated with wellbore structure design, steam injection parameter optimization, and other links. Wellhead uplift prediction and risk assessment will be carried out in the well design stage, and the wellhead uplift risk will be reduced from the source by optimizing the casing structure, cement slurry formulation, steam injection scheme, etc[5].

3. Engineering Prevention and Control Strategies and Research Prospects

In response to the risk of wellhead uplift in offshore thermal recovery wells, scholars and the industry have carried out a lot of research and proposed a series of prevention and control measures, forming an integrated engineering prevention and control strategy covering design optimization, process control, and monitoring and early warning. In the future, with the continuous progress of technology, prevention and control measures will pay more attention to pertinence, effectiveness, and economy.

3.1. Integrated Engineering Prevention and Control Measures

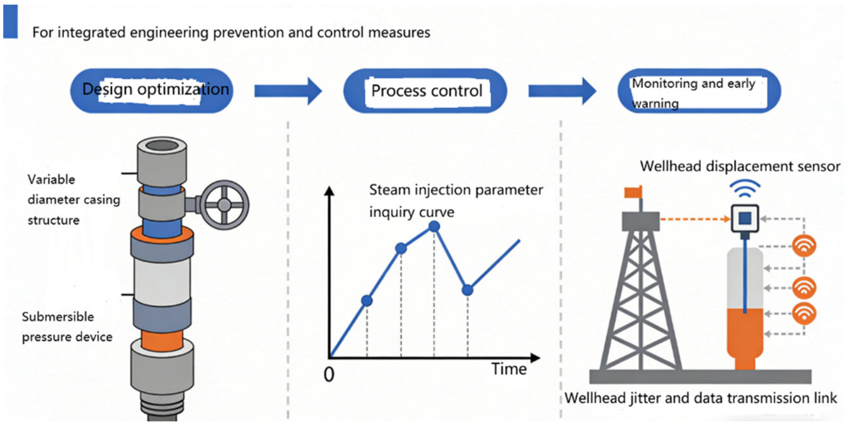

Fig 2. prevention measures flowchart

3.1.1. Design Optimization

Design optimization is the key to reducing wellhead uplift risk from the source. By optimizing the wellbore structure, material selection, cementing process, etc., the anti-uplift capacity of the wellbore system is improved[3]. In terms of casing structure design, variable-diameter casing design can be adopted to increase the stiffness and weight of the lower casing, enhance the anchoring effect, and limit the expansion displacement of the upper casing. At the same time, the connection method of the casing should be reasonably designed, and high-strength and high-toughness casing joints should be used to improve the tensile and deformation resistance of the joints[5]. In terms of material selection, casing materials with low thermal expansion coefficients can be selected to reduce the thermal expansion of the casing. For the cement sheath, the cement slurry formulation can be optimized by adding reinforcing agents such as fibers and nano-materials to improve the bonding strength, toughness, and high-temperature resistance of the cement sheath and delay the occurrence of cement sheath debonding[4].

In terms of cementing process optimization, high-quality cementing technology is adopted to ensure the interfacial bonding quality between the cement sheath and the casing and formation, and improve the interfacial bonding strength[2]. For example, the staged cementing process is adopted to adjust the cement slurry performance according to the characteristics of different well sections to ensure the bonding quality of the cement sheath in each section. During the cementing process, the displacement efficiency of the cement slurry is controlled to avoid problems such as channeling and leakage of the cement sheath and ensure the integrity of the cement sheath[3]. In addition, a pressure relief channel can be set in the annulus or a pressure relief device can be installed, such as a pressure relief valve at the casing shoe. When the annular pressure reaches the set threshold, the pressure relief valve will automatically open to release the trapped pressure and reduce the contribution of annular pressure to wellhead uplift[1]. For example, a new type of casing structure is developed, which connects the trapped annulus with the casing pressure relief space through a pressure relief valve to increase the annular volume change rate and reduce the trapped pressure[5].

3.1.2. Process Control

Process control mainly reduces the driving factors of wellhead uplift and delays the accumulation of uplift by regulating steam injection parameters and production operation methods[3]. In terms of steam injection parameter regulation, the steam injection temperature, pressure, and flow rate should be reasonably controlled to avoid excessively high injection temperature and too fast injection rate[1]. A segmented temperature rise and stepped injection method can be adopted to gradually increase the wellbore temperature, reduce the thermal stress concentration caused by excessive temperature gradient. At the same time, the steam injection cycle is optimized, and the soaking time is appropriately extended to make the wellbore temperature distribution more uniform and reduce the damage of thermal cycling to the casing-cement sheath interface[4].

In terms of annular pressure management, the change of annular pressure should be monitored regularly, and pressure relief measures should be taken in a timely manner[5]. For the sealed annulus, the annular pressure can be controlled within a safe range through manual pressure relief or automatic pressure relief devices. For the non-sealed annulus, the annulus can be kept connected with the atmosphere to avoid pressure buildup[1]. In addition, thermal insulation materials or inert gases can be injected into the annulus to reduce the thermal expansion of the annular fluid and the probability of trapped pressure generation[2]. During the production operation, frequent startup and shutdown of the well should be avoided to reduce the thermal fatigue damage of the casing and delay the expansion speed of cement sheath debonding[4]. In view of the characteristics of thermal recovery wells and high-temperature wells, existing studies have proposed targeted prevention and control countermeasures, which can effectively assist the production resumption of problematic wells[3].

3.1.3. Monitoring and Early Warning

Monitoring and early warning is an important guarantee for timely discovering the risk of wellhead uplift and taking emergency measures[1]. By deploying monitoring equipment, real-time tracking of changes in parameters such as wellhead displacement, wellbore temperature, pressure, and casing stress, an early warning mechanism is established to realize the early identification and timely response of risks[5]. In terms of wellhead displacement monitoring, high-precision monitoring equipment such as laser displacement sensors and GPS positioning systems can be used to real-time measure the uplift and horizontal displacement of the wellhead. At the same time, combined with optical fiber sensing technology, optical fiber sensors are arranged on the casing to monitor the strain distribution of the casing and indirectly reflect the development of wellhead uplift[3].

In terms of wellbore temperature and pressure monitoring, distributed temperature sensing (DTS) systems and pressure sensors are used to real-time obtain temperature and pressure data along the well depth, analyze the evolution laws of the temperature field and pressure field, and predict the development trend of wellhead uplift[2]. A linkage mechanism between monitoring data and prediction models is established. Real-time monitoring data is input into the prediction model to dynamically update the prediction results. When the predicted uplift is close to or exceeds the allowable threshold, an early warning signal is automatically sent to remind operators to take prevention and control measures, such as reducing steam injection temperature, stopping injection for pressure relief, etc., to provide comprehensive guarantee for the safe operation of offshore thermal recovery wells[4].

3.2. Key Influencing Factors and Prevention and Control Focus

Parameter sensitivity analysis shows that injection temperature and cement bonding strength are the most critical factors affecting wellhead uplift[3]. The higher the injection temperature, the greater the thermal expansion of the casing and the more concentrated the thermal stress, which will not only directly increase the wellhead uplift but also accelerate the cement sheath debonding and further exacerbate the uplift[4]. The higher the cement bonding strength, the stronger the constraint effect on the casing, which can effectively limit the expansion of the casing and reduce the wellhead uplift[2]. This means that in engineering practice, the refined regulation of steam parameters and the strict guarantee of high-quality cementing operations are the most effective ways to mitigate the uplift risk[1].

In terms of steam parameter regulation, the optimal steam injection temperature and rate should be determined according to the wellbore structure, formation conditions, and cement sheath performance. Blindly pursuing high-temperature and high-pressure injection to improve recovery rate while ignoring the wellhead uplift risk should be avoided[5]. A quantitative relationship between steam injection parameters and wellhead uplift can be established through numerical simulation and field tests to provide a basis for parameter optimization[3]. In terms of cementing operations, each link such as the formulation design, mixing, pumping, and displacement of cement slurry should be strictly controlled to ensure the bonding quality and integrity of the cement sheath[2]. After cementing, acoustic logging, ultrasonic imaging logging, and other technologies are used to detect the bonding quality of the cement sheath. For well sections with poor bonding quality, remedial measures such as squeeze cementing should be taken in a timely manner to improve the bonding strength of the cement sheath[4].

Practice in preventing and controlling annular pressure buildup shows that different pressure relief methods have different effects. The outward pressure relief method can make the casing safer and has a better maximum allowable annular pressure threshold compared with traditional methods[1]. Therefore, in the selection of pressure relief methods, the outward pressure relief method should be preferred, and the opening pressure and flow parameters of the pressure relief valve should be reasonably designed to ensure the pressure relief effect[5]. At the same time, the pressure relief device should be regularly maintained and inspected to ensure that it can work normally when needed[3]. Future research should further focus on key issues such as the long-term stability of cement sheath bonding performance under high-temperature environments and the refined characterization of multi-field coupling mechanisms under complex thermal cycling conditions, so as to continuously optimize the accuracy and applicability of prediction models[4].

3.3. Research Prospects

Wellhead uplift in offshore thermal recovery wells is a complex nonlinear problem involving the coupling of thermal, mechanical, chemical, and other fields. Although certain progress has been made in mechanism research, prediction technology, and prevention and control measures, there are still many challenges that need further in-depth exploration[3].

In terms of theoretical research, it is necessary to strengthen the refined characterization of multi-field coupling mechanisms under complex thermal cycling, conduct in-depth research on the failure mechanism of the casing-cement sheath interface under the synergistic effect of multiple factors such as high temperature, high pressure, and corrosion, and clarify the initiation conditions, expansion path, and evolution law of debonding[4]. At the same time, quantify the impact of the dynamic marine environment on wellhead uplift, and establish a quantitative relationship between marine environmental parameters and wellhead uplift to provide a more solid theoretical basis for model optimization[2].

In terms of technology research and development, the in-depth integration of prediction technology with intelligent monitoring and adaptive control technology should be promoted to develop an intelligent well system integrating prediction, monitoring, and prevention and control[1]. For example, combined with the Internet of Things technology, the interconnection and data sharing of monitoring equipment are realized. Based on artificial intelligence algorithms, the automatic decision-making and precise execution of prevention and control measures are realized[5]. At the same time, strengthen the research and development and application of new low-cost prevention and control tools, such as new high-efficiency pressure relief valves, degradable packers, high-performance cement slurry additives, etc., to reduce prevention and control costs and improve the economy and universality of prevention and control[3].

In terms of engineering application, strengthen field tests and case analysis, accumulate wellhead uplift data and prevention and control experience under different sea areas, different well types, and different working conditions, and improve the prevention and control measures database[4]. At the same time, establish wellhead uplift risk assessment standards and prevention and control technical specifications to guide engineering practice and improve the standardization level of wellhead uplift prevention and control in offshore thermal recovery wells[2]. Through the in-depth integration of theory, technology, and engineering practice, the safe operation level of offshore thermal recovery wells will be further improved, providing strong guarantee for the efficient development of global offshore heavy oil resources[1].

4. Summary

Wellhead uplift in offshore thermal recovery wells is a key technical problem restricting the safe development of offshore heavy oil resources, and its essence is a complex nonlinear phenomenon under the coupling of thermal, mechanical, and other fields[3]. This paper systematically sorts out the core driving mechanisms of wellhead uplift, and clarifies that uneven thermal expansion is the dominant factor. The constraint difference formed by the active expansion of the upper casing and the anchoring of the lower formation constitutes the core power of wellhead uplift[5]. Trapped annular pressure provides an upward auxiliary force through the end cap effect, which synergistically amplifies the uplift effect with thermal expansion[1]. The dynamic evolution of cement sheath debonding dominates the transformation of the constraint mechanism from bonding to friction, which is the key to the nonlinear characteristics of wellhead uplift[4]. The particularity of the marine environment further amplifies the uplift risk, and the four factors are coupled with each other to form a complex cause system of wellhead uplift[2].

In terms of prediction technology, the traditional method based on the assumption of free casing has been difficult to meet the engineering needs. The multi-field coupling prediction model integrates key factors such as thermal expansion, annular pressure, and interface debonding, and combines the multi-dimensional verification system of "analytical modeling - numerical simulation - physical experiment - field verification" to achieve a significant improvement in prediction accuracy, providing a reliable tool for wellhead uplift risk assessment[3]. In the future, prediction technology will develop in the direction of refinement, intelligence, and integration. By integrating multi-disciplinary technologies, the adaptability to complex working conditions and the timeliness and accuracy of prediction will be further improved[1].

In terms of engineering prevention and control, an integrated strategy covering design optimization, process control, and monitoring and early warning has initially taken shape[3]. Design optimization starts with wellbore structure, material selection, and cementing process to reduce uplift risk from the source[5]. Process control reduces the driving factors of uplift by regulating steam injection parameters and optimizing annular pressure management[1]. Monitoring and early warning realize the early identification and timely response of risks. The three work synergistically to form a comprehensive prevention and control system[4]. Among them, the regulation of steam parameters and high-quality cementing operations are the core of prevention and control, and technical means such as new casing structures and optimized pressure relief methods provide effective support for risk management and control[2].

In general, phased progress has been made in the research on wellhead uplift of offshore thermal recovery wells, but in-depth exploration is still needed in aspects such as the refined characterization of multi-field coupling mechanisms under complex thermal cycling, the quantitative impact of dynamic marine environments, and the research and development of low-cost intelligent prevention and control technologies[3]. In the future, through the in-depth integration of theory, technology, and engineering practice, and the continuous improvement of prediction models and prevention and control strategies, the safe operation level of offshore thermal recovery wells will be further improved, providing a solid technical guarantee for the efficient and green development of global offshore heavy oil resources and promoting the sustainable and healthy development of the petroleum industry in the field of marine energy development[1].

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