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Simulation Study on the Influence of Drag Reducing Agent on Oil Mixing Segment in Product Oil Pipeline Transportation

Yayang Li

School of Pipeline Engineering, Xi'an Shiyou University, Xi'an, Shaanxi 710065, China

Abstract

Drag reducing agents (DRAs) play a vital role in reducing flow resistance, improving transportation efficiency, and saving energy consumption in product oil pipeline transportation. During long-distance transportation, product oil usually operates in a turbulent state, and turbulent fluctuations and energy dissipation inside the fluid are the main causes of pressure drop along the pipeline. As high-molecular polymers, DRAs can interact with turbulent structures, attenuate turbulent fluctuations, and reduce energy loss, thereby achieving drag reduction and throughput enhancement. Meanwhile, DRAs also exert certain effects on fluid viscosity and flow field structure, making the flow regime more stable, which presents favorable engineering application value. In this paper, a numerical model of DRA injection into product oil pipelines is established based on FLUENT software to investigate the flow, mixing, and diffusion processes of DRAs in pipelines. By adjusting parameters such as injection angle, injection pipe diameter, injection flow rate, and injection position, the distribution characteristics of DRAs and their influences on the flow field under different working conditions are compared and analyzed. The results show that a reasonable injection scheme can promote uniform distribution of DRAs in the pipeline and improve the mixing degree with the main flow oil, thus enhancing the drag reduction effect. In summary, focusing on the application of DRAs in product oil pipelines, this paper conducts research from both mechanism analysis and numerical simulation, and analyzes the flow characteristics of DRAs in pipelines and their influence laws on the oil mixing segment. The research results can provide a reference for the optimization of DRA injection modes and the control of product oil batch transportation process, which is of certain engineering significance for improving pipeline operation efficiency and reducing transportation costs.

Keywords

Product Oil Pipeline; Drag Reducing Agent; CFD Numerical Simulation; Mixing and Diffusion; Batch Transportation; Oil Mixing Segment.

1. Introduction

Benefiting from remarkable economic and technical advantages, product oil pipeline transportation systems have achieved continuous scale expansion and technological improvement worldwide. With the rapid development of social economy and the adjustment of energy structure, the total social demand for product oil is rising steadily, and higher requirements are put forward for the rapidity, quality, and low energy consumption of the transportation process.

Among various product oil transportation modes, pipeline transportation has become the preferred scheme to improve transportation capacity due to its high safety, strong continuity, and economic operability. As one of the core technologies of long-distance pipeline transportation, the batch transportation process refers to the continuous transportation of different grades of product oil such as gasoline and diesel in the same pipeline according to a predetermined batch and order, which is a key operation mode to realize efficient pipeline transportation. Batch transportation is also called alternating transportation[1]. Derived from the long-distance crude oil pipeline system, product oil pipeline transportation technology has shown outstanding economic efficiency and technical adaptability after decades of technological iteration and engineering practice. At present, long-distance product oil batch transportation pipelines have become the core carrier of overland product oil transportation in China and globally, playing an irreplaceable key role in ensuring energy supply security, improving transportation efficiency, and reducing operation costs.

By 2013, the total mileage of long-distance product oil pipelines completed and put into operation worldwide had exceeded 365,000 km, 1.2 times that of the crude oil pipeline system, showing a significant leading advantage. Among them, the United States ranks first in the world with 240,700 km of product oil pipelines, and Russia ranks second with 13,700 km. In terms of regional distribution, product oil pipeline resources are highly concentrated in three major regions: North America, South America, and Europe. North America accounts for more than 60% of the total mileage, while Central and South America and Europe have about 18,100 km and 44,600 km respectively, forming the core pattern of global product oil pipeline transportation. The longest product oil pipeline in the world is the Colonial Pipeline in the United States[2]. Represented by the US product oil pipeline system, its batch transportation technology has been highly mature: a single pipeline can continuously transport up to 118 different grades of product oil in batches, usually completing the cyclic transportation of multi-product oil with a complete transportation cycle of 5 days. US product oil pipelines not only rank first in the world in total mileage, but also have the technical characteristics of large inner diameter, multiple injection points, and large transportation capacity in engineering design, and their operation mode represents the advanced level of global product oil batch transportation.

China started the construction of product oil pipelines relatively late. The industrial application of product oil pipeline batch transportation technology in China started relatively late, and large-scale industrial tests were not launched until 1973. In 1976, the Golmud–Lhasa small-caliber long-distance product oil pipeline was officially completed and put into operation, becoming China’s first long-distance product oil pipeline. By the end of 2013, the total mileage of product oil pipelines built nationwide had reached 15,298 km, achieving leapfrog growth in industry scale. Among them, the Lanzhou–Chengdu–Chongqing product oil pipeline put into operation in 2002 is China’s first commercial product oil pipeline with technical characteristics of large caliber, high pressure, long distance, multiple off-take points, multi-product oil transportation, full-line automatic control, and closed batch transportation[3]. Its engineering design and operation level represent the benchmark level of China’s product oil pipeline construction and also the highest level of China’s current product oil pipelines. Overall, compared with energy-developed countries such as Europe and the United States, China’s product oil pipeline construction shows the remarkable characteristics of small total scale, low transportation proportion, and late start of technical system. The overall development level still has an obvious gap with developed countries, with broad room for improvement and development potential.

With the sustainable development of the domestic petrochemical industry, product oil consumption is increasing year by year, and the corresponding storage and transportation costs are also rising. At present, pipeline transportation has become the dominant mode of product oil outward transportation[4]. Compared with road, railway and other transportation forms, pipeline transportation has obvious advantages in space utilization, energy consumption control and climate adaptability.

Product oil mostly operates in a turbulent state in long-distance pipelines, and the drag reduction effect of high-molecular DRAs can be effectively exerted in turbulent flow fields. Its drag reduction mechanism originates from the interaction between polymer macromolecules and turbulent structures, which can effectively suppress pulsation dissipation. Adding DRAs into the pipeline can reduce pressure loss along the route, achieving energy saving and consumption reduction under constant flow rate, or improving transportation capacity under the same energy consumption level, thus realizing the dual goals of energy saving and throughput increase[5].

Pipeline transportation has become the main mode of long-distance product oil transportation[6]. According to the calculation of Sinopec Economics and Development Research Institute, China’s domestic terminal consumption of product oil was 404 million tons in 2024[7]. However, fluid transportation in pipelines will produce significant turbulent loss, so injecting high-molecular polymer DRAs with excellent long-term drag reduction effect is the key to improving transportation volume and reducing energy consumption[8][9].

For existing long-distance product oil pipelines, adding DRAs is the most economical, flexibly adjustable and stably operated preferred technical means to achieve energy saving and efficiency increase without additional equipment. At present, there are various types of DRAs in the field of long-distance pipelines[10][11]. However, most researches on DRA performance focus on indoor loops or crude oil pipelines, and few are carried out through product oil pipelines. Therefore, carrying out research on the influence of various factors on the effect of DRAs in product oil pipelines can not only fill the research gap of DRA effects under different pipeline operation conditions, but also provide theoretical support and practical guidance for production units to optimize DRA operation schemes combined with actual working conditions, which has important engineering application value[12][13].

There are many parameters affecting the effect of DRAs, among which the characteristics of DRAs themselves are the core influencing factors. For example, in terms of molecular structure, linear and spiral DRAs have significantly better drag reduction efficiency than star and comb structures; the shear resistance of DRAs directly determines the durability of their effects, and the stronger the shear resistance, the longer the drag reduction effect lasts; in terms of injection concentration, with the increase of DRA mass fraction, the drag reduction effect gradually increases, but there is an optimal threshold, beyond which the drag reduction effect no longer improves significantly.

During the actual operation of long-distance pipelines, pipeline body parameters such as pipe diameter, pipe wall roughness and pipeline length, as well as auxiliary equipment such as supporting pump sets, heating furnaces and DRA injection devices are fixed, and the type of DRA is also determined. Therefore, for long-distance pipelines that have been completed and put into operation, the key influencing parameters that can be independently selected and easily measured only include DRA injection mass fraction, oil properties (such as oil density and viscosity), and pipeline operation parameters (flow rate)[14][15].

Therefore, studying the injection mode and angle of DRAs is of practical application significance for the application of DRAs in product oil pipelines.

Product oil pipeline transportation occupies a core position in product oil outward transportation with remarkable advantages such as low transportation cost, strong operational reliability, continuous transportation, outstanding transportation capacity and low oil loss rate, and also has a good protective effect on the ecological environment.

The product oil batch transportation process can promote the full-load and efficient operation of long-distance pipelines, which not only can effectively improve the economic benefits of enterprises, but also alleviate the transportation pressure of other transportation modes such as road and railway, with significant engineering application value. However, this process also has obvious limitations: mixing occurs at the contact interface of different batches of transported oil, forming an oil mixing segment[16]. The physical and chemical properties of this oil mixing segment are different from those of the two kinds of product oil before and after, so it cannot be sold as qualified product oil, resulting in certain oil loss and economic loss. This phenomenon not only adversely affects the transportation quality of product oil, but also causes corresponding economic losses. Therefore, carrying out research on the formation and influencing factors of oil mixing segments in product oil pipeline batch transportation has very important practical application value and realistic significance for reducing oil mixing loss, improving the safety of pipeline transportation, and improving social and economic benefits.

At present, researches on product oil batch transportation are mainly divided into two categories: theoretical research and experimental research. Although experimental research has the prominent feature of objective results, it is easily restricted and disturbed by various external factors in the actual development process, and requires a lot of human, material and financial resources, making the economic investment of the whole research always maintain a high level. Taking the actual operation of the Kuybyshev–Bryansk product oil pipeline as an example, when the pipeline transports diesel and gasoline with a viscosity difference of nearly 9 times, the difference in oil mixing volume caused by different transportation sequences can reach up to 10%.

With the rapid development of computer technology, the theoretical research mode of product oil batch transportation has gradually transformed from traditional formula analytical calculation to numerical simulation. Numerical simulation has gradually developed into a core research method in the field of product oil batch transportation with the prominent advantages of convenience, flexibility, low cost, green and pollution-free, as well as visual and intuitive simulation results. Kang Zhengling et al[17]. studied the influence of height difference on oil mixing in vertical pipelines; Wu Yuguo et al[18]. carried out numerical simulation of oil mixing characteristics in elbows for batch transportation of hot and cold crude oil by using PHOENICS software; Zhao Haiyan[19] analyzed the oil mixing segment of batch transportation by using FLUENT software, adopted a non-reactive multi-component transport model to analyze the influence of various working conditions such as oil transportation speed, transportation sequence, shutdown, blind branch pipes and circular arc transition right-angle elbows on oil mixing, and analyzed the influence of gravity field on oil mixing in inclined pipelines. Zhang Qingsong[20] used PHOENICS software to carry out numerical simulation of oil mixing in special working conditions of batch transportation in right-angle elbows and blind branch pipes. From the perspective of CFD software application[21], PHOENICS software mainly focuses on the simulation of low-speed heat flow transport phenomena; mainstream international CFD software includes FLUENT, STAR-CD and CFX-TASCflow, among which FLUENT software accounts for about 40% of the market share, and has become the most widely used and influential CFD software at present with its leading advantages in sliding grid technology, turbulence model, multiphase flow model and other aspects.

2. Application Status of Drag Reducing Agents

Since DRAs were first applied to crude oil transportation pipeline systems in 1979, drag reduction technology has developed extremely rapidly. Adding DRAs in oil pipeline transportation can significantly reduce the friction resistance of pipeline systems, improve pipeline transportation capacity, reduce the transportation cost of long-distance pipeline systems[22][23][24], and further improve the safety and reliability of pipeline operation. Most DRAs are water-soluble or oil-soluble high-molecular polymers, which are functional additives that can significantly reduce fluid transportation resistance with only a small amount of addition. At present, there are many hypotheses about the mechanism of action of DRAs in academic circles, among which the turbulent fluctuation suppression hypothesis has been widely recognized by many scholars. This hypothesis holds that high-molecular polymers can achieve drag reduction through dual effects: on the one hand, inhibiting the generation of vortices in turbulence and reducing fluid fluctuation intensity; on the other hand, suppressing axial turbulence intensity and reducing turbulent energy loss, ultimately achieving the goal of reducing transportation resistance[27][28][29][30].

Musharah et al[31]. showed that macromolecules in DRAs are susceptible to shear during pipeline transportation, but even after shearing, their molecular weight can still be maintained at a high level. When these macromolecules enter the engine with product oil, thermal degradation is prone to occur, and incomplete combustion may occur, thereby forming deposits on key components of internal combustion engines (such as fuel injectors, intake valves, etc.).

Li et al[33]. found that the drag reduction effect increases with the increase of Reynolds number; Quan et al., Shi Pengfei et al[34]., Liu Feifan et al[34]. found that the drag reduction rate increases with the increase of polymer concentration; Huo Miaomiao et al[35]., Wang Chunxiao et al[36]. pointed out that drag reduction effect cannot be achieved when the relative molecular weight of polymer is less than 10^5, and the drag reduction effect increases with the increase of polymer concentration until the saturation concentration is reached, after which the drag reduction effect begins to decrease; Guan Xinlei et al[37]. believed that there is strong strain outside the viscous bottom layer of near-wall turbulence, which stretches the polymer long chains, causing an increase in effective viscosity, thereby suppressing turbulent fluctuations and producing drag reduction effect; Soares et al[38]., Ru Chun et al[39]. found that solvent solubility and quality will affect the polymer drag reduction effect.

Non-standard injection operation of DRAs, retention and accumulation at a certain part of the pipeline, or unreasonable control of pipeline operating pressure will lead to abnormally high concentration of DRAs in product oil or insufficient shearing of DRAs. If such problems are not detected and handled in a timely manner, they will adversely affect the quality of product oil and affect its service performance. At present, in the field of product oil pipeline transportation in China, DRAs are often used in the pipeline transportation process of diesel; while gasoline has low viscosity and small flow resistance during pipeline transportation, so the method of adding DRAs has not been adopted in gasoline pipeline transportation at present.

In the gasoline–diesel mixed transportation pipeline system, after the transportation of diesel containing DRAs is completed, if gasoline is continuously transported, the residual DRAs on the inner wall of the pipeline may be carried by gasoline, thereby affecting the quality of gasoline. Based on this, carrying out research on quality control methods in product oil pipeline transportation has important engineering significance and practical value for ensuring the transportation quality of both gasoline and diesel.

Up to now, only a small number of relevant literatures have been reported, mainly exploring the impact of DRAs on the physical and chemical properties of diesel through on-site additive tests of pipelines and laboratory simulated shear tests[40][41].

3. Applied Research on Drag Reducing Agents

Wang Li[14] carried out research on drag reduction effect evaluation of product oil batch transportation pipelines, and proposed to take friction coefficient as the core evaluation index by comparing and analyzing transportation characteristics under different operating parameters. Compared with traditional evaluation methods such as benchmark pressure and flow conversion, friction coefficient can more scientifically and accurately reflect pipeline drag reduction efficiency and throughput increase effect, and then objectively characterize the actual level of drag reduction rate and throughput increase rate, providing a reliable basis for pipeline operation optimization.

Zhou Hongtai[42] focused on polyacrylamide and its derivative high-viscosity DRAs for hydraulic fracturing engineering needs, and systematically explored their performance and engineering application effects. This type of DRAs has excellent sand-carrying performance, good thermal stability and low reservoir damage. Applying it to hydraulic fracturing construction of unconventional oil and gas reservoirs can effectively ensure the smooth development of construction and show good on-site application results, providing technical support for the development of unconventional oil and gas reservoirs.

Liu Bo[15] used the DRA injection function module of Stoner Pipeline Simulator software to carry out systematic evaluation research on the drag reduction effect of a fixed-flow pipeline. The research results show that injecting DRAs at the pipeline outlet can effectively reduce the shearing effect of related equipment in the station on DRAs, avoid the attenuation of efficiency caused by excessive shearing of DRAs, and further achieve the engineering goal of pipeline drag reduction and throughput increase, providing a reference for the actual operation optimization of pipelines.

Li Hairong[43] carried out practical application research of DRAs on an oilfield site in Iraq. Under the working conditions of aging pipelines and unable to further improve the transportation efficiency of external transmission pumps, injecting DRAs with a concentration of 20 mg/L effectively achieved the goal of drag reduction and throughput increase, and achieved significant economic benefits, providing a practical technical path for the efficient operation of old pipelines.

Ding Fei[44] carried out research on the drag reduction effect of polyacrylamide in hydraulic fracturing. In view of the characteristics of large burial depth and high formation temperature of deep shale reservoirs, higher requirements are put forward for the high-temperature resistance of DRAs for fracturing. Pure polyacrylamide itself has good temperature resistance stability, but it is prone to oxidative degradation in an oxygen-containing environment, leading to a significant decline in its drag reduction efficiency. Modifying polyacrylamide by polymerizing temperature-resistant functional monomers can effectively improve its high-temperature resistance and oxidation resistance, thereby significantly enhancing the drag reduction effect of DRAs, providing technical support for deep shale hydraulic fracturing construction.

Lin Yonggang[10] carried out research on drag reduction and throughput increase on the Wusu–Shanshan pipeline, and found that adding 10 ppm DRA can achieve a throughput increase rate of 9%–28%.

Pan Zibo et al[45]. carried out industrial application test research on the drag reduction effect of DRAs with the Fuxing–Bayu product oil pipeline as the actual application carrier. The test results clearly show that DRAs can play a significant drag reduction role in different types of product oil, and the drag reduction effect has a positive correlation with the addition concentration.

Specifically, in 93# gasoline, when DRA addition concentration is 10 mg/L, pipeline transportation drag reduction rate can reach 14.9%; when addition concentration is increased to 15 mg/L, drag reduction rate is further increased to 18.7%, and drag reduction effect is significantly enhanced; in 0# diesel, the effect of DRAs is more obvious. When adding 10 mg/L DRA, drag reduction rate can reach 23.3%, and when addition concentration is increased to 15 mg/L, drag reduction rate rises to 27.7%, effectively achieving the goals of reducing transportation energy consumption and improving transportation efficiency, providing technical support for the efficient operation of pipelines.

Toms first discovered and studied the polymer drag reduction phenomenon in 1948, so the polymer drag reduction phenomenon is also called the “Toms effect”. Although the research and development and engineering application of DRAs have gone through more than 30 years of development[46][47], due to their extremely strict performance requirements on the molecular structure of high-molecular polymers, such as relative molecular weight reaching more than one million, excellent shear resistance, and high non-crystalline characteristics to ensure rapid dissolution and dispersion in oil systems, the number of enterprises that can scale up production of DRA polymers meeting on-site application standards is very limited.

In the field of DRA research and development and production, a few enterprises centered on Conoco Company and Baker Hughes Company of the United States control the core technical voice in this field, forming a certain technological monopoly pattern. The DRA products researched and produced by these two enterprises not only lead the current development trend of DRA technology, but also represent the top level in the global field.

In 1979, Conoco Company of the United States took the lead in applying its independently developed Dg200 DRA to the western product oil long-distance pipeline project. The actual application data shows that the DRA can reduce pipeline friction by 40% and achieve a 28% increase in transportation volume, significantly improving pipeline transportation efficiency. In 1990, Baker Hughes Company of the United States further expanded its product matrix, researched and produced various types of DRAs, which have a wide range of applications and can adapt to various transportation media such as crude oil with different wax contents, various product oils (including diesel, kerosene, gasoline) and liquefied petroleum gas, meeting the drag reduction needs under different working conditions[48][49].

In the past two decades, Conoco Company and Baker Hughes Company have made breakthrough progress in key indicators such as drag reduction performance and stability of DRA products. Their researched and developed DRA products have been widely recognized and applied on a large scale in the international market with excellent performance. Among them, Conoco Company has taken the lead in carrying out systematic experimental research on the impact of DRAs on oil quality since the 1990s, laying a foundation for the practical application of DRAs.

To verify the impact of DRAs on engine operation, researchers carried out long-term tests on diesel engines using diesel added with 30 ppm concentration of DRAs, while using diesel engines without DRAs as controls. The test results show that diesel engines using this concentration of DRAs for a long time do not have any abnormal working conditions and can maintain stable and normal operation, proving that DRAs will not adversely affect engine operation.

In addition, in the field test carried out on the product oil pipeline in Colorado, researchers added DRAs with a concentration of 20–80 ppm into the pipeline. The test detection data shows that at the contact interface of two different oils, the DRA content is lower than 1 ppm, which is almost undetectable. The test results confirm that adding DRAs to a single oil will not interfere with another oil, and can effectively ensure the batch transportation of multiple oils, providing a reliable experimental basis for the wide application of DRAs in batch transportation pipelines[50][51]. Baker Hughes has also successively developed FLO, FLO-XL, FLO-XS and other DRAs, and their drag reduction performance has been greatly improved.

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