Optimization of Mixing Crude Oil Density for Batch Transportation Based on Sales Benefit

Yan Shang, Xiaokai Xing, Hanhua Yang, and Ming Yang

Abstract To improve sales efficiency from upstream pipeline companies and ensure the supply of high-quality crude oil for downstream refineries, it is necessary for pipeline companies to progressively realize the interconnection of oil and gas long-distance pipelines. Under this background, the batch transportation of different quality crude oil will be the development trend in the future. The quality of crude oil determines the selling price, which is closely related to the density. Therefore, it is worthy for pipeline companies to dig into how to control the mixing proportion of different crude oil to ensure the maximization of crude oil sales benefits. Taking the distribution system of an oil field as an example, this paper first analyzed the profit and loss law of high-quality oil during batch transportation. Then, based on the maximization of crude oil sales benefit, an objective programming model was established to optimize crude oil allocation. Finally, this paper proposes the optimum density limit for crude oil batch transportation by discussing the influence of mixing crude oil density on the supply, profit, and loss. The optimized result of the oil field's transportation and distribution system shows it can significantly increase the crude oil sales profit when the mixing crude oil density of medium I crude oil is between 868 and 869 kg/m^3, and medium II crude oil is about 889 kg/m^3. This conclusion has also been verified in the field, and achieved good application results.

Keywords Crude oil · Batch transportation · Mixed oil · Optimization of density · Field application

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Nomenclature

A	Front crude oil during batch transportation.
S	Crude oil profit and loss.
B	Subsequent crude oil during batch transportation.
C_i	Sales price of each mixed crude oil.
i	$i = 1 \sim m$, represents the type of oil after blending, and m is taken as 2 in the paper.
x_j	Number of types of crude oil mixing.
j	$j = 1 \sim n$, represents the quantity of oil from the block, and n is taken as 6 in the paper.
q_j	Oil volume from each block.
g_i	Profits and losses of crude oil during batch transportation, m^3.
Z	Composite variable.
K_A	Concentration of the front oil in the contamination.
d	Inner diameter of pipe, m.
K_B	Concentration of the front oil in the contamination.
L	Pipe length, m.
Re	Reynolds number.
ρ_I, ρ_{II}	Medium I/II density, m^3.
Re_{pj}	Average Reynolds number.
B_j	All quantities of j crude oil.
α	Correction coefficient, the smaller the Reynolds number, the higher the value of α.
Q	Pipeline throughput.
I	Medium oil I.
$Q-$, $Q+$	Minimum/maximum allowable throughput of pipeline.
II	Medium oil II.
k_0	Maximum number of selected crude oil.
p_j	Average value.
$x-$, $x+$	Lower/upper limit of crude oil blending ratio.
L	Number of types of crude oil mixing.

1 Introduction

In recent years, pipeline companies have been developing an integrated network to secure energy supply and improve energy utilization, while promoting the development of the oil and gas industry towards high quality and low emissions. As part of this trend, the separate storage, transmission, and refining process has become increasingly popular, and the batch transportation of different quality crude oils is becoming more common. In the production and marketing of crude oil, density is one of the main indicators to evaluate the quality of crude oil, and its level is closely related to its trade settlement, light oil yield, and smooth operation of refinery units [1, 2]. Therefore, determining the optimal blending ratio of different crude oils and controlling the mixed oil density to ensure maximum benefits from crude oil sales is a priority issue for crude oil marketers. At present, the relevant studies of mixed crude oil mainly analyze the oil physical properties changes from the operation safety point of view, while few studies are carried out from the economic point of view. The study of the physical properties, such as gel point, viscosity, and rheology of mixed crude oil has attracted the attention of many researchers in universities, research institutes, and oil companies. The existing models for calculating the gel point of mixed crude oil are mainly empirical or semi-empirical formulas derived by researchers based on experimental data, such as Li's model [3], Liu's model [4, 5], Chen's model [6, 7], and others. For heavy and extra-heavy crude oils, it is necessary to accurately measure the viscosity of the oil sample before transportation and take appropriate measures to reduce viscosity [8]. Experimental determination of viscosity of crude oil and petroleum products can be performed according to standardized methods such as ASTM D88, ASTM D445, ASTM D2170, ASTM D7042. Fan [9] considered analyzing the physical changes of blended crude oil to determine whether it has the stability and safety required for pipeline transmission. Yu [10] proposed to change a pipeline from sequentially transporting six types of crude oil to two. This change is mainly influenced by the constraints of oil sources, refinery transmission capacity, and factors such as the wide variation in the nature of oil products and the complexity of the transportation process. All of the above studies were conducted from the perspective of pipeline safety to study the changes in oil properties after mixing different grades of crude oil. Xie et al. [11–13] thought that crude oil density directly affects the actual quantity and transaction amount of delivered oil products, and then established different models for calculating the density of mixed crude oil. They blended two crude oils in five different proportions, then analyzed the experimental results and concluded that the densities of the blended crude oils conformed to the linear summation law [11]. The deficiency of this experiment was only for blending of two oils, so it could not be demonstrated whether it was applicable to blending of multiple oils. Shu et al. [13] referred to the calculation model of viscosity, gel point and yield value of mixed crude oil. Combining with experimental data, they respectively put forward the density model of mixing thin oil with thin oil and heavy oil with thin oil. In general, the above researches on the density of mixed crude oil clarify the correlation between crude oil density and sales efficiency, but only provide some calculation methods for the density of mixed crude oil, rather than effectively linking the profit from crude oil sales with the density. From the perspective of oil processing safety and refining efficiency maximization, some scholars have conducted studies related to blended crude oil ratios [14–18]. Li et al. [14] established a crude oil production scheduling optimization model. But the model was not applicable to the case of mixing multiple crude oils which only considered the case of mixing two types of crude oil. Li et al. [15, 16] established a new model for crude oil scheduling operations considering the optimization problems of ship demurrage and crude oil inventory management, but their non-convex mixed integer model is difficult and slow to solve. Liang et al. [17] assumed that the basic properties of crude oil remained unchanged when crude oil was mixed, and used the real boiling point distillation data as the main quality index to evaluate the properties of crude oil. Since this assumption does not match the actual situation, the resulting model cannot be applied to the field. Hou [18] took northern Shaanxi crude oil as an example, taking the maximum total yield of mixed crude oil distillation products as the main goal, and established a crude oil ratio model. The above researches on blending determined that crude oil ratios are from a downstream refining perspective. Through literature reading, the model which established by controlling the mixing ratio of oil to improve the sales efficiency of crude oil is rarely seen.

This paper focuses on the crude oil distribution system in the eastern operating area of a certain oil field. The organizational structure of this article is as follows. Section 2 introduces the current situation of the crude oil pipeline transportation and distribution system in the region. Section 3 analyzes the effect of density on the profit and loss of crude oil batch transportation after various types of crude oil blending. Section 4 proposes various optimization models for crude oil blending density based on the maximization of crude oil sales benefits. Section 5 uses the crude oil blending model to determine the optimal density limit for the sequential transportation of crude oil in the transportation and distribution system. Finally, Sect. 6 presents the conclusions and outlook for future research.

2 Current Situation of Distribution and Transportation System in a Region

Crude oil is typically classified into four categories based on its density: light oil, medium I, medium II, and heavy oil. The density ranges for each quality of crude oil are outlined in Table 1, in accordance with relevant standards. The density of crude oil is a key factor in determining its market price, with lower density crude oils commanding higher prices.

The crude oil produced in the target oil region comes from six blocks and is classified into four types based on its density: light oil, medium I, medium II, and heavy oil. Due to limited oil sources, the pipeline operates at a low throughput. Moreover, the physical properties of multiple crude oils can vary significantly, making batch transportation more complex, especially during winter when corresponding transport

Table 1 Correspondence table of crude oil quality grade and density

Crude oil quality grade	Density ranges (kg/m^3)
Light oil	< 846
Medium I crude oil	846–870
Medium II crude oil	870–910
Heavy oil	> 910

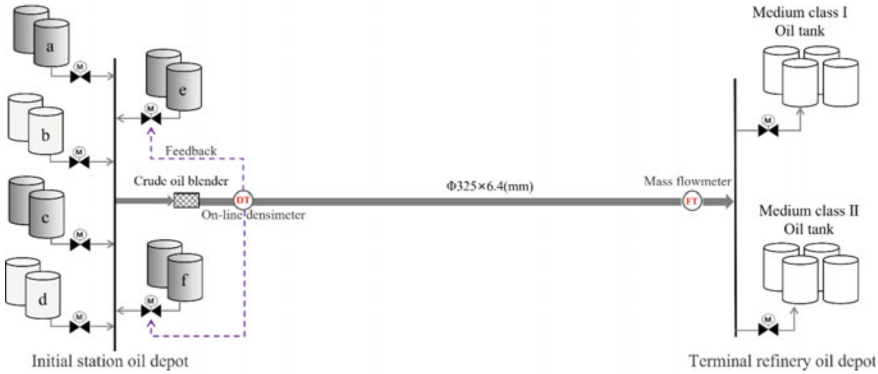

Fig. 1 Process flow diagram of distribution system

plans must be developed for each oil type based on their physical characteristics. This leads to a constant alternation of cold and hot crude oil in the pipeline, which is detrimental to pipeline safety and energy efficiency. To ensure safe and energy-efficient operation, the initial station oil depot mixes the oil from the six blocks into medium I and medium II crude oil, given the relatively small quantities of light and heavy oil. However, the current method of determining the mixed oil density is based solely on empirical values, resulting in a wide range of changes. The crude oil is transported to the terminal refinery oil depot through a 160 km export pipeline. And the pipe specification is Φ325 × 6.4 (mm), working pressure is 3.6 MPa. The terrain along the pipeline is flat, with negligible elevation differences between the starting point and the terminal point. Figure 1 shows the process flow diagram of the distribution and transportation system in the oil region, where crude oil from the six operation areas is stored in corresponding storage tanks before being transported to the terminal refinery oil depot. A mass flow meter and block valve are installed in front of the tank to regulate the flow of crude oil. The Crude oil blender is used to mix several types of crude oil evenly, while an On-line densimeter monitors the density of the mixed crude oil. If the density exceeds the standard, the On-line densimeter controls the opening of different valves. At the end of the pipeline, the oil density is measured manually by taking samples, and a two-part cutting technique is used for oil switching.

3 Profit and Loss Analysis of Batch Transportation

According to the established standard for oil classification, crude oil is divided into two categories: medium quality I and medium quality II, based on a density threshold of 870 kg/m^3. Crude oil with a density of 870 kg/m^3 or less is classified as medium quality I, while crude oil with a density greater than 870 kg/m^3 is classified as medium quality II.

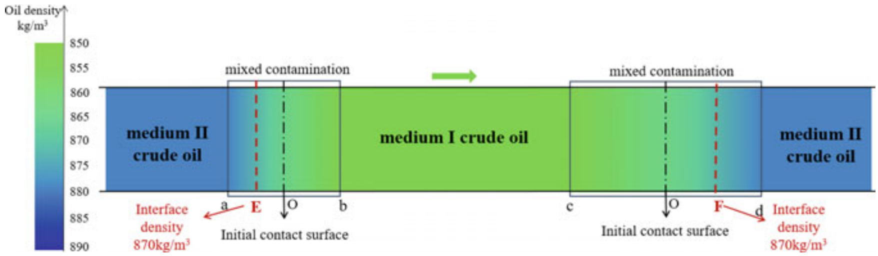

Fig. 2 Schematic diagram of oil cutting at low oil distribution density

When the oil density is low, and the density of the initial contact surface between two types of crude oil (calculated as the arithmetic mean of the densities of the two products before and after mixing) is less than 870 kg/m^3, the cutting interface is positioned closer to the medium II crude oil side. This results in more blended oil being settled at the price of medium I crude oil. The blended oil volume of EO and FO segments is the surplus of medium quality I oil, as shown in Fig. 2. At the endpoint cost calculation of the pipeline, medium I crude oil generates additional profits.

When the oil density is high and the initial contact surface density between two types of crude oil is greater than 870 kg/m^3, the cutting interface is positioned closer to the medium I crude oil side. This results in a greater volume of blended oil being settled at the price of medium II crude oil. As shown in Fig. 3, the mixed oil in the OE and OF sections represents a deficit volume of medium quality I crude oil. That is, the amount of received Medium Grade I crude oil is less than what is transported, which is detrimental to crude oil sales.

It can be seen that from the perspective of mixing loss, the lower oil blending density, the larger the quality margin of medium I crude oil. Therefore, mixing some medium grade II oil with medium quality I oil and settling at the same price enhances crude oil sales efficiency. However, from the perspective of oil distribution volume, the lower the oil distribution density, the less the distribution of high-quality oil products, leading to lower crude oil sales revenue. Hence, the actual receiving amount of medium I crude oil at the terminal refinery oil depot is determined by the amount of oil delivered and the profit and loss during batch transportation. To

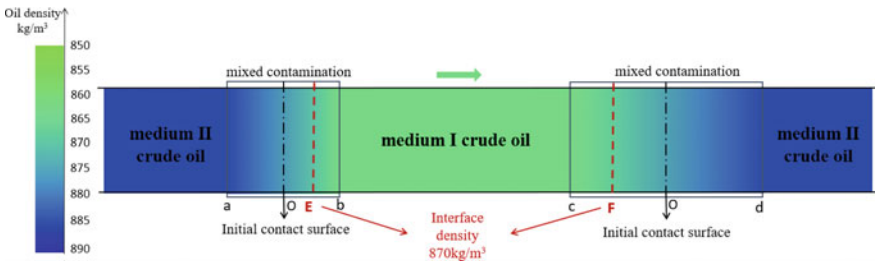

Fig. 3 Schematic diagram of oil cutting at high oil distribution density

maximize sales benefits, it is necessary to optimize the blending ratio of each type of crude oil and the oil distribution density of medium I crude oil.

4 Optimization Model of Crude Oil Mixing Density

The total sales revenue of crude oil at the terminal station mainly comprises the oil allocation value of medium I and medium II crude oil at the initial station and the profit and loss (P&L) of oil during transportation.

The objective function can be expressed by the following mathematical formula:

$$\max S(x) = \sum_{i=1}^{m} C_i \sum_{j=1}^{n} x_j q_j + \sum_{i=1}^{m} C_i g_i \tag{1}$$

where the left-hand side shows the total revenue; the first term on the right-hand side represents the value of medium I and medium II crude oil after blending at the initial station, and the second term represents the profit and loss of crude oil during transportation, where profit is positive and loss is negative. Assuming a crude oil throughput of q_1, q_2, …, q_n for each block, the mixing ratio for each crude oil in preparing medium I crude oil is x_1, x_2, …, x_n, $0 \le x_j \le 1$. Similarly, the mixing ratio for preparing medium II crude oil is $1 - x_1$, $1 - x_2$, $1 - x_n$, $0 \le 1 - x_j \le 1$. The selling price of each type of crude oil is C_i (i = 1, 2, …, m). In this optimization, various types of crude oil are blended to produce medium I and medium II crude oil, thus m = 2; g_i (i = 1, 2) represents the profit and loss volume of crude oil during transportation, and the profit is positive, m^3.

The model does not include the pipeline transportation cost, which can be regarded as a fixed value for the crude oil allocation problem with the total amount unchanged. And it has little impact on the optimization results.

4.1 Determination of Oil Profit and Loss

According to the turbulent diffusion theory [19], the oil concentration K_A and K_B are functions of the comprehensive variable Z, and their relationship can be expressed by Eq. 2. The integration constants C_1 and C_2 can be obtained from the following boundary conditions: at any given moment $0 < t < \infty$, when $x = 0$, $K_B = 0.5$ and $Z = 0$; at any cross-section $0 < x < \infty$, as t approaches 0, $K_B = 0$, *and* $Z = \infty$.

$$K_B = C_1 \int_0^Z e^{-Z^2} dZ + C_2 \tag{2}$$

Substituting the initial and boundary conditions into Eq. 2 and using Taylor expansion, the probability integral function can be calculated.

$$\phi(Z) = \frac{2}{\sqrt{\pi}} \int_0^Z e^{-Z^2} dZ = \frac{2}{\sqrt{\pi}} \left[Z - \frac{1}{1!}\frac{Z^3}{3} + \frac{1}{2!}\frac{Z^5}{5} - \frac{1}{3!}\frac{Z^7}{7} + \cdots \right] \tag{3}$$

$$K_A = \frac{1}{2}[1 + \phi(Z)] = \frac{1}{2}\left[1 + \phi\left(\frac{x}{2\sqrt{D_T t}}\right)\right] \tag{4}$$

$$K_B = \frac{1}{2}\left[1 - \phi\left(\frac{x}{2\sqrt{D_T t}}\right)\right] \tag{5}$$

Based on polynomial fitting to approximate the inverse function, we obtained the solution by applying the least-squares method.

$$Z = 25.94K_A^3 - 52.85K_A^2 + 37.33K_A - 8.77 \tag{6}$$

The correlation coefficient $R^2 = 0.97$, the fitting result is good.

$$g_i = \pi \alpha Z d^{\frac{5}{2}} L^{\frac{1}{2}} \sqrt{\frac{3 \times 10^3 + 60.7\mathrm{Re}_{pj}^{0.545}}{\mathrm{Re}_{pj}}} \tag{7}$$

where g_i represents the profit and loss volume of crude oil during transportation, and the profit is positive, m^3; α is correction coefficient; d is pipe inner diameter, m; L is pipe length, m; Re_{pj} is average Reynolds number.

4.2 Density Constraints of Medium I and Medium II Crude Oil

$$846 \leq \rho_{\mathrm{I}} \leq 869 \tag{8}$$

$$870 \leq \rho_{\mathrm{II}} \leq 889 \tag{9}$$

$$\rho_{\mathrm{I}} = \frac{\sum_{j=1}^{n} x_j \rho_j q_j}{\sum_{j=1}^{n} x_j q_j} \tag{10}$$

$$\rho_{\mathrm{II}} = \frac{\sum_{j=1}^{n} \left(1 - x_j\right) \rho_j q_j}{\sum_{j=1}^{n} \left(1 - x_j\right) q_j} \tag{11}$$

Constraints on crude oil allocation:

$$\sum_{j=1}^{n} x_j q_j \leq B_j \tag{12}$$

where B_j represents all quantities of the jth crude oil.

Pipeline throughput constraint:

$$Q = \sum_{i=1}^{m} \sum_{j=1}^{n} x_j q_j + \sum_{i=1}^{m} g_i \tag{13}$$

$$Q- \leq Q \leq Q+ \tag{14}$$

where Q is pipeline throughput; Q− is the minimum allowable throughput of the pipeline; Q+ is the maximum allowable throughput of the pipeline.

Constraints on maximum crude oil variety:

If too many kinds of crude oil involved in mixing, there are certain difficulties in actual operation. In order to make the model more suitable for on-site deployment, the maximum number of crude oil varieties is added.

$$\sum_{l=1}^{L} k_l \leq k_0 \tag{15}$$

where L is number of crude oil involved in blending; k_0 is the maximum number of selected crude oil.

Proportioning constraint:

$$x- \leq x \leq x+ \tag{16}$$

where x− is lower limit of crude oil blending ratio; x+ is the upper limit of crude oil blending proportion. The actual operation conditions shall be taken into account during crude oil blending. Only when such crude oil is required to be greater than a certain amount can it be blended.

5 Example Analysis

The oil of target oil region comes from 6 blocks, covering four types including light oil, medium I, medium II and heavy oil. Considering that the quantity of light oil and heavy oil is relatively small, the initial station oil depot will mix all kinds of crude oil into medium I and medium quality II. And five days is a cycle. The density and quantity of each batch oil from 6 blocks are shown in Table 2. Pipeline transportation constraint is 175 m^3/h $\leq$ Q $\leq$ 498 m^3/h. The blending ratio is restricted to 10–100%. And the number of mixed crude oil varieties is restricted to $2 \leq \sum_{l=1}^{L} k_l \leq 4$.

To fully utilize the oil quality margin, it is important to distribute as much high-quality oil as possible to improve sales efficiency. This means that the oil distribution density of medium II crude oil should be controlled to approach the upper limit of density. When the oil distribution density of medium I crude oil is high, the initial contact surface density of the two oils exceeds 870 kg/m^3, resulting in most of the mixed oil being cut to medium II crude oil. As shown in Fig. 4a, the losses of medium quality I crude oil, O′E and O′F, are relatively large. On the other hand, when the oil distribution density of medium I crude oil is low, the initial contact surface density of the two oils is slightly higher than 870 kg/m^3. During cutting, the loss of medium I crude oil (O″E and O″F) is relatively small, as shown in Fig. 4b.

Table 2 Crude oil information

Block name	Product	Oil density (kg/m^3)	Throughput (t/batch)
Block a	q_1	843	4000
Block b	q_2	848	4900
Block c	q_3	878	7000
Block d	q_4	885	8000
Block e	q_5	914	2900
Block f	q_6	888	5500

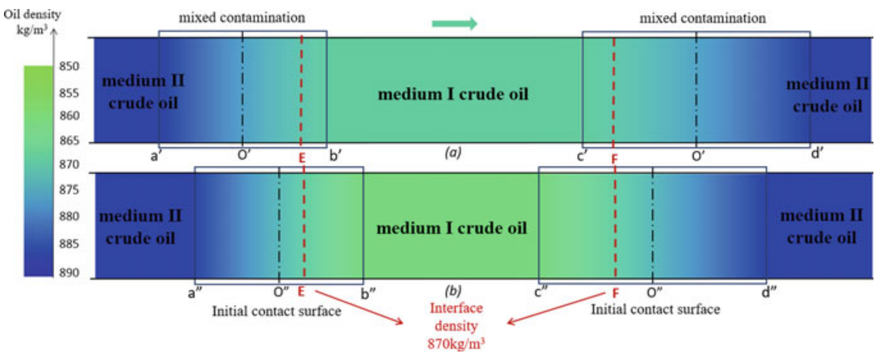

Fig. 4 Schematic diagram of oil cutting in the calculation example

Take the sales price of crude oil in a certain place in October 2021 as an example, as shown in Table 3. The model is solved based on the above data, and the results are shown in Table 4 and Fig. 5.

As shown in Table 3, when the total amount of crude oil is fixed, the higher the oil distribution density of medium I crude oil, the greater the quantity of medium I crude oil that is blended, while the quantity of medium II crude oil that is blended decreases. We can see from Fig. 5 and Table 4 that increasing the mixing oil density of medium I crude oil results in more losses caused by batch transportation. However, the increase in oil distribution density of medium I crude oil leads to a much larger change in oil distribution volume than in loss volume. Therefore, the distribution density of medium I crude oil increases, and the receiving volume of medium quality I oil at the terminal station shows an increasing trend as the distribution density of medium I crude oil increases. As shown in Fig. 5, with the total amount of crude oil unchanged, the total sales revenue of crude oil will increase along with the medium I crude oil volume. This model is applied to the mixing of various kinds of crude oil in this area, and the optimal oil distribution density limit is used for oil mixing. By using this optimization model to control the mixing proportions of different crude oils, the volume of medium I crude oil can be blended to the maximum extent. Based

Table 3 Transaction price of crude oil in a place

Crude oil quality	Transaction price (CNY/t)
Light oil	3660
Medium I crude oil	3439
Medium II crude oil	3277
Heavy oil	2994

Table 4 Results of optimal oil blending under different densities

No.	ρ_{I} (kg/m^3)	ρ_{II} (kg/m^3)	x_1	x_2	x_3	x_4	x_5	x_6	Q_I (t/batch)	Q_{II} (t/batch)	S (million CNY)
1	860	889	1	1	0.38	0.41	0	0	14,899	17,401	108.65
2	861	889	1	1	0.33	0.51	0	0	15,454	16,846	108.81
3	862	889	1	1	0.29	0.62	0	0	16,041	16,259	108.99
4	863	889	1	1	0.24	0.74	0	0	16,681	15,619	109.20
5	864	889	1	1	0.18	0.87	0	0	17,378	14,922	109.44
6	865	889	1	1	0.14	1	0	0	18,137	14,163	109.71
7	866	889	1	0.94	0.29	1	0	0	18,969	13,331	110.04
8	867	889	1	0.88	0.46	1	0	0	19,885	12,415	110.42
9	868	889	1	0.81	0.64	1	0	0	20,900	11,400	110.89
10	869	889	1	0.73	0.84	1	0	0	22,034	10,266	111.46

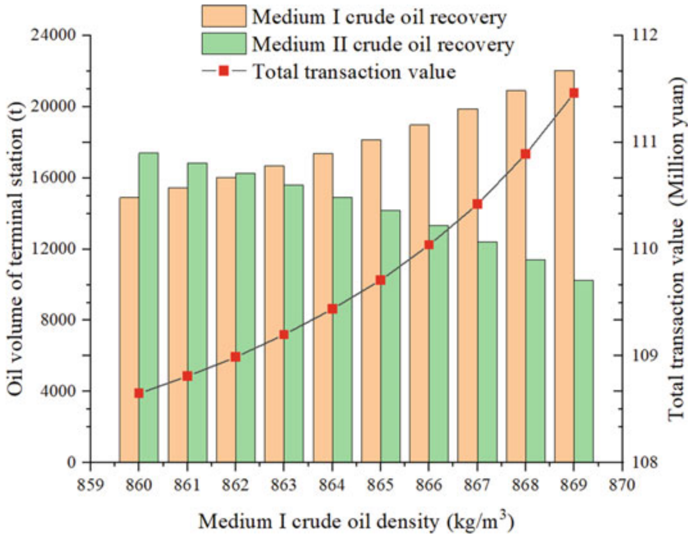

Fig. 5 Comparison chart of oil receipts and total transaction volume of medium I and medium II crude oil under different working conditions

on a one-year follow-up analysis, the resulting annual revenue increase from sales benefits is approximately 4.8 million yuan.

To sum up, considering some uncontrollable factors in on-site oil distribution, it is recommended that the oil distribution density of medium I crude oil is between 868 and 869 kg/m^3, and 889 kg/m^3 for medium II crude oil.

6 Conclusions

(1) This study introduces a new concept of net profit and loss of crude oil mixture during batch transportation, providing novel insights for tackling the mixing issue in sequential crude oil transportation. In the batch crude oil transportation process, mixing may result in either losses or gains, depending on factors such as blending density and threshold at the first station, blending volume, mixing along the way, and settlement standards of crude oil.

(2) Based on a constrained multiple linear prediction optimization model, the optimal oil blending density for crude oil alternating transportation is determined. For the crude oil distribution system in this region, the higher the blending density of high-quality oil during alternating transportation, the greater the amount of oil allocated to the first station's oil depot, and the greater the loss of mixed oil during cutting. Overall, the increase in oil allocation far exceeds the increase in mixed oil loss. Therefore, increasing the high-quality oil blending density at the first station in this region can significantly improve the sales

benefits of crude oil. It is recommended that the density limits for medium I and medium II crude oil are 868–869 kg/m^3 and 889 kg/m^3, respectively, which can increase sales revenue by approximately 4.8 million yuan annually.

(3) In our future research, we will refine the optimization model and make it programmable with a user interface that allows input of basic information for a given area to obtain the optimal oil blending density, blending ratios of each type of oil, and maximum crude oil sales efficiency. This will greatly facilitate the use of the system by on-site personnel.

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