Tran. Natl. Acad. Sci. Azerb. Ser. Phys.-Tech. Math. Sci.
Mechanics, **45** (7), 43–53 (2025);
https://doi.org/10.30546/2706-7734.45.7.2025.043

Analysis of the sequential transportation of oil batches with different viscosities through a technological segment of a main oil pipeline

Radmir R. Tashbulatov · Rinat M. Karimov · Jiaqiang Jing · Jie Sun · Ramil N. Bakhtizin

Received: 12.10.2024 / Revised: 23.03.2025 / Accepted: 18.05.2025

Abstract. *This paper presents an approach to optimizing the transportation of two crude oils with differing viscosities by forming two batches and pumping them sequentially through a segment of a trunk pipeline. The study accounts for the effect of viscosity on flow rate and demonstrates that, under certain assumptions, only two strategies are practically feasible: full blending or sequential pumping without intermixing. It is shown that the closer the viscosity–composition relationship is to linear additivity, the more energy-efficient the sequential mode becomes. A selection criterion based on laboratory measurements is proposed. A practical method is developed for choosing the optimal strategy, considering operational constraints and the required transportation schedule.*

Keywords. sequential pumping · compounding · crude oil blending · multi-grade crude mixture · optimal blending · high-viscosity crude · energy efficiency

Mathematics Subject Classification (2010): 76B07

1 Introduction

According to the forecast for the scientific and technological development of Russia's fuel and energy sector until 2035 [1], one of the long-term priorities in oil production may be the extraction of heavy and viscous crude oils, the reserves of which are vast in Russia. These reserves are estimated at 7 billion tons, ranking Russia third in the world after Canada and Venezuela. Importantly, these resources are located in regions with well-developed infrastructure originally established for conventional oil production (in the European part of Russia, Western Siberia, and Sakhalin). In principle, the development of such fields is economically more attractive and can be implemented in relatively short timeframes compared to the creation of safe offshore hydrocarbon extraction technologies in the Arctic seas' harsh ice conditions or automated underwater (under-ice) production complexes with competitive

R.R. Tashbulatov, R.M. Karimov, Jiaqiang Jing, Jie Sun and R.N. Bakhtizin
Ufa State Petroleum Technological University
E-mail: karimovrinat@mail.ru

economic indicators. According to the same document [1], the most promising method for transporting heavy and viscous crude oil is blending it with light crude oils. The authors of this paper have repeatedly proposed methods for optimal formation of crude oil flows with differing rheological properties to minimize total pumping costs [2–4], essentially introducing new compounding approaches based on viscosity parameters. These approaches have already begun to be implemented at the Ukhta-1 pumping station (PS) of the Ukhta-Yaroslavl main oil pipeline for the Yarega field crude oil, where a blending unit and all necessary infrastructure for pumping this oil were constructed (insulated tanks, heating stations, pumping stations with screw pumps, etc.) [5]. Oil blending at the Ukhta-1 PS is carried out based on density and viscosity.

The work presented in [6] attracted considerable interest from the authors of this paper. It demonstrated that, as an alternative to dilution and blending of crude oils with differing viscosities, in some cases it may be more advantageous or cost-effective to transport the oils sequentially or to form special batches of mixtures, which should also be pumped sequentially. The proof of this assertion was based on the assumption of constant pumping capacity. However, changes in the viscosity of the transported product cause significant variations in flow rate within the technological segment of the main oil pipeline [7–9].

It should be noted that even if sequential pumping of crude oils or specially formulated mixtures with differing viscosities within a single technological segment is not advantageous, in the broader context of optimizing crude oil flow formation for an entire main pipeline system - as discussed in [10] - there may arise scenarios where it is more efficient to deliver viscous oil components without blending at one mixing node. In such cases, these components are transported as a separate batch to the next mixing node, where dilution with lower-viscosity components takes place. This approach allows direct delivery of viscous components to sections of the branched trunk pipeline system that are less sensitive to viscosity increases in terms of energy consumption. Thus, to complement the flow formation problem with the possibility of sequential pumping of viscous crude components, it is necessary to solve the problem of optimal selection of mixing concentrations for specially prepared oil batches for their sequential transportation within a single technological segment of the main pipeline, taking into account the variation in pumping flow rate for each batch.

2 Theory

21 Problem statement

In [6], it is noted that the problem of optimizing the composition of crude oil mixtures in batches formed for sequential pumping through a technological segment of a pipeline can have four possible solutions:

1 formation of a single batch of crude oil mixture with concentrations corresponding to the delivery shares specified in the pumping plan;
2 formation of two separate “pure” batches, each consisting entirely of oil from one supplier (no mixing);
3 formation of two batches where one is created by blending a portion of the less viscous oil into the more viscous oil batch, and the other consists of the remaining less viscous oil;
4 blending a portion of the more viscous oil into the less viscous oil batch, with subsequent pumping of the remaining more viscous oil as a separate batch.

It is necessary to note that a more general blending scenario should be considered and included, wherein not only one of the original crude oils is blended, but both. This results in the formation of two batches with viscosities differing from those of the original oils. The four cases described above are essentially special cases of this more general blending scenario.

For convenience, the more viscous oil will be denoted by the subscript 1, and the less viscous oil by the subscript 2. The concentration defining the mixture composition is taken as the mass fraction of the less viscous oil in the mixture. Thus, the original oil ¹1 has a concentration of 0, and oil ¹2 has a concentration of 1. The concentration of the mixture corresponding to the delivery share in the pumping plan is determined by the formula:

$$x_{mix} = \frac{M_2}{M_1 + M_2} \tag{2.1}$$

where M_1 and M_2 are the initial masses of the more viscous and less viscous crude oils, respectively, that must be transported through the technological segment according to the pumping plan within a fixed time period. Then, the mass balance for pumping crude oils from two suppliers [6] should be supplemented as follows:

$$\sum M = M_1 + M_2 = (M_1 + \Delta M_2 - \Delta M_1) + (M_2 + \Delta M_1 - \Delta M_2) \tag{2.2}$$

where ΔM_1 and ΔM_2 are the portions of the masses of the more viscous and less viscous crude oils, respectively, required for dilution of the original oils and formation of new mixture batches for their sequential pumping through the technological segment of the main pipeline.

$(M_1 + \Delta M_2 - \Delta M_1)$ - mass of the newly formed batch No.1;

$(M_2 + \Delta M_1 - \Delta M_2)$ - mass of the newly formed batch No.2.

Concentrations of the newly formed batches No.1 and No.2, respectively:

$$x_1 = \frac{\Delta M_2}{M_1 + \Delta M_2 - \Delta M_1} \tag{2.3}$$

$$x_2 = \frac{M_2 - \Delta M_2}{M_2 + \Delta M_1 - \Delta M_2} \tag{2.4}$$

The optimization problem consists in determining such mixing concentrations x_1 and x_2 of the newly formed crude oil batches that, when pumped sequentially through a single technological segment of the main pipeline, minimize the total energy consumption for transportation.

22 Influence of the Composition of a Batch Formed from Crude Oils with Different Viscosities on Its Energy Consumption During Transportation

The energy consumption of pump units operating in a pump-to-pump configuration, required to transport crude oil with mass *M*, is determined by the formula [6 - 9]:

$$E = \sum_{i=1}^{n} N_i \tau = \sum_{i=1}^{n} \rho g \frac{H_i Q}{\eta_i} \tau = \sum_{i=1}^{n} \rho g \frac{H_i V}{\eta_i} = gM \sum_{i=1}^{n} \frac{H_i}{\eta_i} \tag{2.5}$$

where *Q* is the steady-state flow rate of crude oil in the technological segment of the main pipeline;

$N_i,\ H_i,\ \eta_i$ – are the power consumption, head, and efficiency of the *i*-th pump unit at flow rate *Q*;

τ is the pumping duration;

ρ is the density of the transported crude oil;

n is the number of operating pump units.

Changes in the viscosity of the transported product directly affect the pumping flow rate. The steady-state flow rate of crude oil in the technological segment of the main pipeline should be determined from the pressure balance equation [7 – 9], which equates the pressure developed by the pump units and the pressure consumed by the pipeline. The latter can be calculated using the well-known Leibenzon formula [6 – 9]:

$$\sum_{i=1}^{n} H_i = \sum_{i=1}^{n} \left(a_i - b_i Q^2\right) = \beta \frac{Q^{2-m} v^m}{D^{5-m}} L. \tag{2.6}$$

where $\beta,\ m$ are coefficients of the Leibenzon equation [9], depending on the corresponding turbulent flow regime;

ν is the kinematic viscosity of the transported product;

D is the internal diameter of the pipeline;

L is the equivalent (calculated) length of the technological segment;

$a_i,\ b_i$ are approximation coefficients of the head curve for the *i*-th centrifugal pump.

Equation (2.6) defines the relationship between the change in flow rate within the technological segment of the main pipeline and the viscosity of the transported crude oil batch. For calculating energy consumption using formula (2.5), the dependence of the pump unit efficiency is represented by the following equation [9]:

$$\eta_i = c_i Q + d_i Q^2 + e_i Q^3 \tag{2.7}$$

where $c_i,\ d_i,\ e_i$ are approximation coefficients from the characteristic curve of the *i*-th centrifugal pump. Thus, having determined the flow rate *Q* from equation (2.6) depending on the viscosity variation of the crude oil batch, the energy required to pump the mass *M* should be calculated using the formula

$$E = gM \sum_{i=1}^{n} \frac{\left(a_i - b_i Q^2\right)}{c_i Q + d_i Q^2 + e_i Q^3} = gMH_\eta \tag{2.8}$$

$H_\eta = f(Q)$ - the energy required per unit weight of the transported fluid for pumping at flow rate *Q*:

$$H_\eta = \sum_{i=1}^{n} \frac{\left(a_i - b_i Q^2\right)}{c_i Q + d_i Q^2 + e_i Q^3} \tag{2.9}$$

The dependence of the mixing concentration on the viscosity of the mixture is well approximated by the formula [10–15]:

$$Lg\left(Lg\left(v + c\right)\right) = x \cdot Lg\left(Lg\left(v_1 + c\right)\right) + (1 - x) \cdot Lg\left(Lg\left(v_2 + c\right)\right) \tag{2.10}$$

x - concentration of oil in the mixture.

It should be noted, based on previous studies [11–14], that the viscosity of the mixture is non-additive and exhibits varying curvature depending on the concentration of the blended crude oils. The curvature of the viscosity dependence of a binary mixture can be estimated using the following formula:

$$Y = 2 \cdot \frac{\left(v_{1/2} - v_2\right)}{v_1 - v_2} \tag{2.11}$$

The closer the value of *Y* is to one, the more pronounced is the linear additivity of the mixture's viscosity. Studies [ ] have observed that *Y* typically ranges from 0.5 to 0.8.

23 Problem Solution

For further analysis of the total energy consumption during the pumping of two specially formed crude oil batches, a quantity referred to as the mass imbalance ratio is required:

$$Dis = \frac{\Delta M_2 - \Delta M_1}{M_1 + M_2} \tag{2.12}$$

Considering formulas (2.3) – (2.4), we obtain:

$$Dis = \frac{x_1\left(x_2 - x_{mix}\right) - \left(1 - x_2\right)\left(x_{mix} - x_1\right)}{x_2 - x_1} = x_{mix} + \frac{x_1 - x_{mix}}{x_2 - x_1} \tag{2.13}$$

Essentially, the mass imbalance ratio indicates the extent to which the mass ratio of the specially formed crude oil batches planned for pumping is artificially shifted through blending of the original oils. The difference between the mixture concentration corresponding to the planned supply share and the mass imbalance ratio should be referred to as the shifted mass fraction of batch No. 2 relative to the total mass of the original crude oils.

$$x_{mix}^{'} = x_{mix} - \ Dis = \frac{x_{mix} - x_1}{x_2 - x_1} = \frac{\left(M_2 + \Delta M_1 - \Delta M_2\right)}{M_1 + M_2} \tag{2.14}$$

When planning batch-wise pumping, it is necessary to consider that changes in the flow rates of individual batches relative to the flow rate of a single mixture affect the completion time of the scheduled pumping task. Therefore, the search should be limited to such mixing concentrations for the newly formed crude oil batches whose sequential pumping can be completed within the planned execution time:

$$\frac{M_1 + \Delta M_2 - \Delta M_1}{\rho_1 Q_1} + \frac{M_2 + \Delta M_1 - \Delta M_2}{\rho_2 Q_2} \le \tau_{run} \le \frac{M_1 + M_2}{\rho_{mix} Q_{mix}} \cdot k \tag{2.15}$$

where $\rho_1,\ \rho_2$ are the densities of the newly formed batches No 1 and No 2, respectively;

ρ_{mix} is the density of the mixture with concentration corresponding to the planned supply share;

$Q_1,\ Q_2$ are the steady-state flow rates for pumping batches No 1 and No 2, respectively, determined from equation (2.7);

Q_{mix} is the steady-state flow rate for pumping the mixture with concentration corresponding to the planned supply share;

k is the time margin coefficient for completing the scheduled task relative to pumping the original crude oils as a single mixture (greater than one).

From equation (2.15), we obtain the following constraints for the search of optimal concentrations:

$$x_{mix}^{'} = \frac{x_{mix} - x_1}{x_2 - x_1} \le \frac{\frac{\rho_{mix} Q_{mix}}{\rho_1 Q_1} - k}{\frac{\rho_{mix} Q_{mix}}{\rho_1 Q_1} - \frac{\rho_{mix} Q_{mix}}{\rho_2 Q_2}} \tag{2.16}$$

To estimate the total energy consumption for pumping two crude oil batches, we use the equivalent energy per unit weight of the transported fluid, $H_{mix}^{\eta'}$, required for pumping all batches of crude oil, which can be determined from the following relation:

$$gM_1 H_1^{\eta} + gM_2 H_2^{\eta} + g\Delta M_1\left(H_2^{\eta} - H_1^{\eta}\right) + g\Delta M_2\left(H_1^{\eta} - H_2^{\eta}\right) = H_{mix}^{\eta'}\left(M_1 + M_2\right) \tag{2.17}$$

Considering (2.13), we obtain:

$$H_{mix}^{\eta'} = H_1^{\eta}\, x_{mix}^{'} + H_2^{\eta}\left(1 - \ x_{mix}^{'}\right) = H_1^{\eta}\, \frac{x_{mix} - x_1}{x_2 - x_1} + H_2^{\eta}\left(1 - \frac{x_{mix} - x_1}{x_2 - x_1}\right) \tag{2.18}$$

Since the formula is linearly additive with respect to $x^{'}_{mix}$, and this quantity according to formula (2.14) essentially represents the displacement fraction of the concentration of the selected batch No 1, x_1, relative to x_{mix} over the entire range $(x_2 - x_1)$, the following geometric consideration applies. A point on the straight line connecting the values H^{η}_{1} and H^{η}_{2}, corresponding to x_1 and x_2 for the dependence $H_{\eta} = f\,(x)$, defined by formulas (2.6), (2.9), and (2.10), which lies above the value x_{mix}, will correspond to $H^{\eta^{'}}_{mix}$.Fig. 1 illustrates an example of determining $H^{\eta^{'}}_{mix}$.

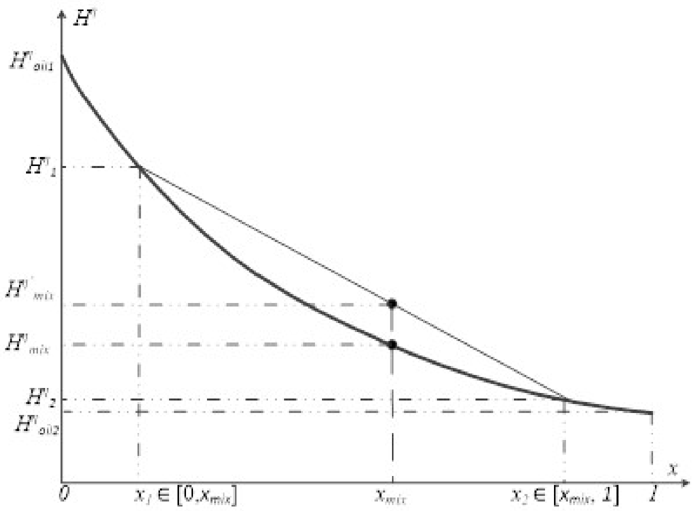

Fig. 1. Method for determining the equivalent normalized energy for pumping crude oil in batches

Fig. 1 clearly shows that the solution to the problem of finding the optimal mixing concentrations of specially formed crude oil batches depends on the convexity or concavity of the dependence $H_{\eta} = f\,(x)$. For fixed parameters of the pipeline section and pump equipment characteristics, as well as known viscosities of the original mixtures, the shape of the function $H_{\eta} = f\,(x)$ depends on the parameter *Y*.

The shape of the function $H_{\eta} = f\,(x)$, defined by formulas (2.6), (2.9), and (2.10), depending on the parameter *Y*, is shown in Fig. 2. The function $H_{\eta} = f\,(x)$ exhibits two inflection points when approaching a linear dependence. In other cases, the function is either concave $Y \ll 1$ or convex ($Y \approx 1$). Since the deviation of energy consumption in the case with two inflection points from a linear dependence is small, it can be neglected, as the effect of selecting optimal mixing strategies will be minor. It is possible that these inflection points are caused by the empirical functions (2.6) and (2.10) and do not occur in reality. However, if one were to find a purely mathematical solution for this case, it would be most advantageous to form two batches: leaving the less viscous oil No 2 unchanged, and diluting the more viscous oil No 1 to a concentration close to 0.25. As noted, the effect, if any, will be minimal.

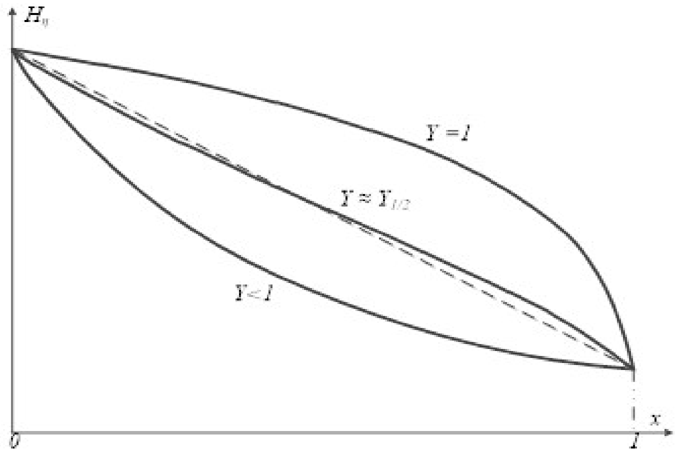

Fig. 2. Dependence of the function $H_\eta = f(x)$ on the parameter Y

In other cases, the solution to the above problem reduces to either pumping the oils as a single unified mixture or pumping them in separate ”pure” batches, i.e., without performing any blending operations. Thus, a criterion is needed to determine which mode of pumping is more energy-efficient: sequentially or as a unified mixture.The criterion $Y_{1/2}^{'}$ can be determined by solving the equation where a 1:1 mixture yields the following value of $H_\eta\,(0,5)$ according to equations (2.6), (2.9), and (2.10).

$$H_\eta\,(0,5) = \frac{H_{oil1}^{\eta} + H_{oil2}^{\eta}}{2}$$

To solve the above problem, it is necessary to:

1 Measure the viscosity of the initial oils and the viscosity of the mixture at a mixing ratio of 1:1 (x = 0.5); calculate the value of $Y_{1/2}$.
2 Using the measured viscosities of the initial oils and the parameters of the technological section with the installed pumping equipment, calculate the values of H_{oil1}^{η} , H_{oil2}^{η} and $H_\eta\,(0,5)$.
3 Determine the criterion $Y_{1/2}^{'}$ and compare it with $Y_{1/2}$. If $Y_{1/2}^{'}$more, than $Y_{1/2}$, pumping as a single mixture is more advantageous; if less, then sequential pumping in separate batches is preferable. If the values are close, the energy consumption for pumping in a single mixture or sequentially will be approximately the same.
4 In the case of selecting sequential pumping, it is necessary to verify constraint (2.16). If the constraint is not satisfied, then the option of diluting the more viscous oil should be chosen until the condition for completing the planned pumping within the specified time is met.

To verify the validity of the theoretical foundations presented, numerical calculations were performed to determine the function *H* depending on x_1 and x_2 for various NM-brand pumps, whose characteristics are provided in [9]. The calculation results were consistent with the theoretical considerations described above. Examples of these calculations are shown in Fig. 3–5.

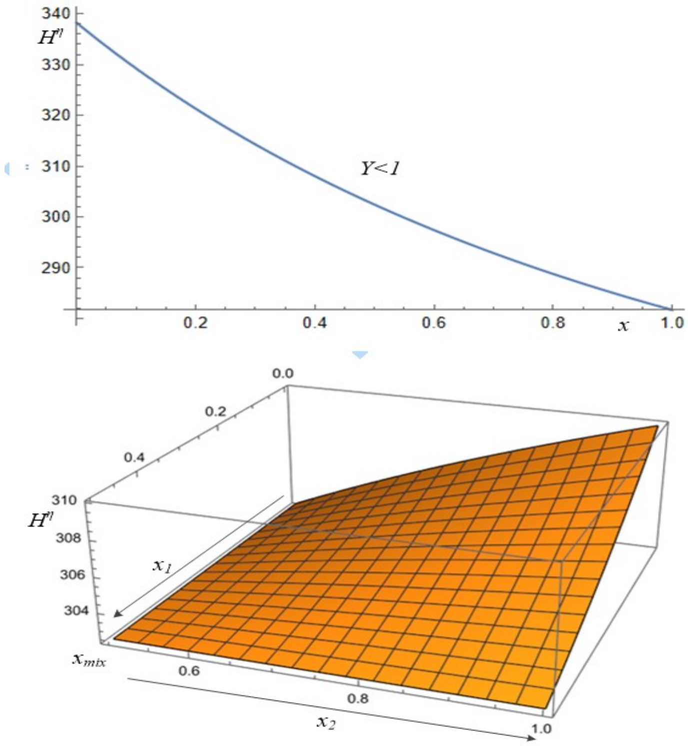

Fig. 3 – Example of a numerical solution for H() across the entire range when $Y < 1$

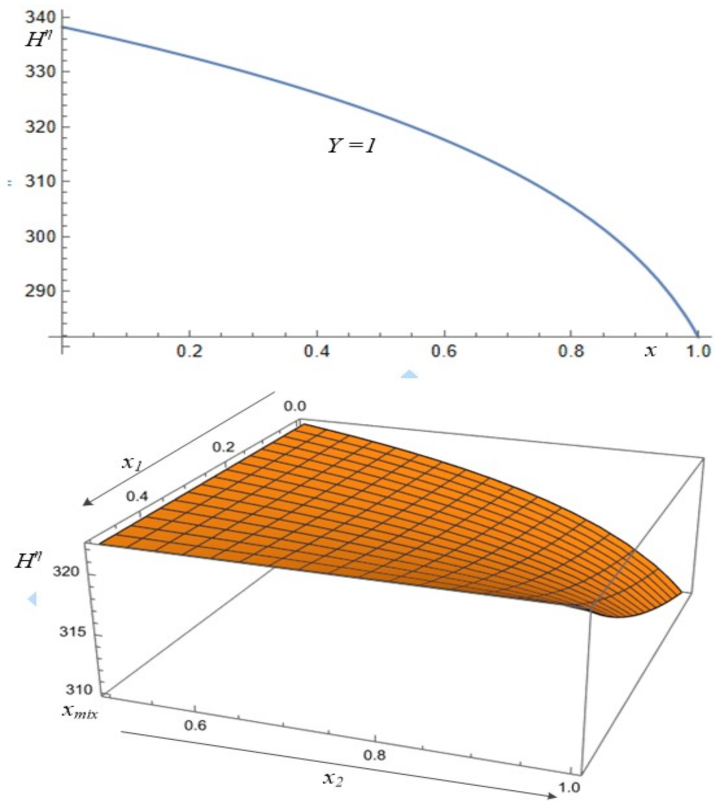

Fig. 4 – Example of a numerical solution for H() across the entire range when $Y \approx 1$

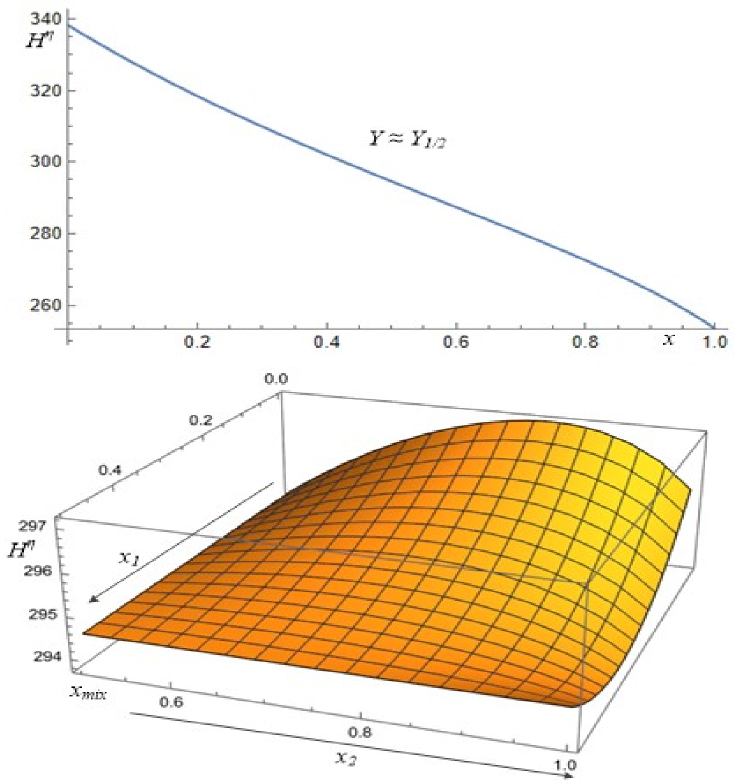

Fig. 5 Example of a numerical solution for H across the entire range when $\mathbf{Y} \approx \mathbf{Y_{1/2}}$

3 Discussion

The solution to the stated problem is based on the assumption that the pumping regimes remain constant throughout the execution of the scheduled task. However, the conclusions drawn remain valid even when the regimes vary. It is simply recommended that, in the case of sequential pumping, less viscous oil be conveyed during lower operating regimes, and more viscous oil during higher regimes.

The technical feasibility of using a tank farm to accumulate specific batches was not considered. Nevertheless, we believe that the additional energy expenditure associated with switching between batches is negligible compared to the overall energy consumption, and that even relatively frequent switches—due to limited tank farm capacity—should not materially affect the choice of pumping strategy.

Based on the derived equations, forming a third (or additional) batch when only two initial crude oils are involved will always be impractical. However, when blending three or more crude oils, the optimal strategy is not immediately evident and warrants further investigation.

4 Conclusion

1 It has been theoretically demonstrated that the optimal pumping strategy for batches of crude oils with differing viscosities reduces to choosing either a single unified mixture or separate "pure" batches, based on the proposed criterion.

2 A criterion is introduced to determine the feasibility of sequentially pumping specially formulated oil batches with different viscosities. This requires laboratory measurements of the viscosities of the original oils and of a 1:1 blend.

The solution to this specific problem is intended to augment the more general optimization framework for allocating crude oil flow streams with varying viscosities so as to minimize total energy consumption [10].

5 Acknowledgment

The research was carried out with the support of a grant from the Eurasian Scientific and Educational Center (project No. ENOC-06-22).

References

1. Prognoz nauchno-tekhnologicheskogo razvitiya otrasley toplivo-energeticheskogo kompleksa Rossii na period do 2035 goda / Ministerstvo energetiki Rossiyskoy Federatsii, 2016.
2. Tashbulatov R.R. Razrabotka metodiki provedeniya mnogomernoy optimizatsii energopotrebleniya sistemy magistral'nykh nefteprovodov za schet formirovaniya gruzopotokov nefti razlichnykh mestorozhdeniy / Tashbulatov R.R., Karimov R.M., Valeev A.R., Mastobaev B.N. // Neftyanoye khozyaystvo. 2020. ¹ 6. S. 98–103.
3. Karimov R.M. Povysheniye energoeffektivnosti perekachki za schet perepasledleniya gruzopotokov i optimalnogo smesheniya reologicheski slozhnykh neftey / Karimov R.M., Tashbulatov R.R., Mastobaev B.N. // Transport i khraneniye nefteproduktov i uglevodorodnogo syr'ya. 2017. no 3. p. 13–18.
4. Tashbulatov R.R. Uzlovaya reologicheskaya zadacha smesheniya neftey dlya optimal'nogo raspredeleniya gruzopotokov v razvetvlennoy seti nefteprovodov / Tashbulatov R.R., Karimov R.M., Valeev A.R., Mastobaev B.N. // Nauka i tekhnologii truboprovodnogo transporta nefti i nefteproduktov. 2018. T. 8, ¹ 5. S. 532–539.
5. Lyapin A.Yu. Otsenka vliyaniya uvelicheniya priema yaregskoj nefti na kachestvo gruzopotokov v sisteme magistralnykh nefteprovodov / Lyapin A.Yu., Bakanov A.V., Astakhov A.V. // Nauka i tekhnologii truboprovodnogo transporta nefti i nefteproduktov. 2022. 12(1), 87–93.
6. Kutukov S.E., Bazhaykin S.G., Golyanov A.I. Povysheniye effektivnosti posledovatel'noy peråêàchki optimizatsiyey komponentnogo sostava smesi neftey // Neftyanoye khozyaystvo. 2018. no 1. p. 88–91.
7. Lur'ye M.V., Mastobaev B.N., Revel'-Muroz P.A., Soshchenko A.E. Proektirovaniye i ekspluatatsiya nefteprovodov, 2019.
8. Tugunov P.I., Novoselov V.F., Korshak A.A., Shammazov A.M. Tipovyye raschety pri proektirovanii i ekspluatatsii neftebaz i nefteprovodov: ucheb. posobiye dlya vuzov. Ufa: OOO "DizaynPoligrafServis", 2002.
9. Korshak A.A., Nechval' A.M. Proektirovaniye i ekspluatatsiya gazonefteprovodov: ucheb. dlya vuzov. SPb: Nedra, 2008.
10. Tashbulatov R.R., Karimov R.M. Energosberegayushchaya metodika peråêàchki neftey razlichnykh mestorozhdeniy po razvetvlennoy sisteme magistral'nykh nefteprovodov / Svidetelstvo o registratsii EVM.
11. Tashbulatov R.R., Karimov R.M., Mastobaev B.N., Valeev A.R. Analiz izmeneniya vyazkostno-temperaturnoy zavisimosti binarnoy neftyanoj smesi // Transport i khraneniye nefteproduktov i uglevodorodnogo syrya. 2018. no 2. p. 5–9.

12. Tashbulatov R.R., Karimov R.M. Sravnitelnyy analiz tochnosti primenyayemykh modeley vyazkostno-temperaturnykh zavisimostey pri reshenii zadach truboprovodnogo transporta // Truboprovodnyy transport – 2017: tez. dokl. XII Mezhdunar. ucheb.-nauch.-prakt. konf. Ufa: Izd-vo UGTU, 2017. p. 189–191.
13. Tashbulatov R.R., Karimov R.M. Prognozirovaniye reologicheskikh svoystv smesey pri sovmestnom truboprovodnom transporte neftey // Truboprovodnyy transport uglevodorodov: mater. Vseross. nauch.-prakt. konf. s mezhdunar. uchastiem. Omsk: Izd-vo OmGTU, 2017. S. 88–91.
14. Tashbulatov R.R. Prognozirovaniye vyazkostno-temperaturnykh kharakteristik techeniya smesey pri sovmestnoy transportirovke razlichnykh neftey v sisteme magistralnykh nefteprovodov: dis.... kand. tekhn. nauk: 25.00.19 / Tashbulatov Radmir Rasulevich. Ufa, 2019. 135 p.