Hydraulic Design of New Composite Polyurethane Oil Transfer Hose

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Abstract: To ensure a reasonable and cost-effective design pressure for the new composite polyurethane (PU) oil transfer hose, this study presents a mathematical model and hydraulic friction calculation formulas that account for variations in hydraulic friction resulting from the decrease in the elastic modulus. The hydraulic grade line of the PU hose exhibits a nonlinear equation with continuous curvature changes. To address this, we investigate a specific mathematical description method and employ numerical calculation methods to computerize the graphical calculation process. Additionally, the study examines the new pressure energy balance relationship in various transportation scenarios, such as fluctuating flow rates and cross-station transport, laying the groundwork for optimizing the operation plan.

Keywords: design pressure, hydraulic friction, elastic modulus, pressure energy balance

1 Introduction

Amid ongoing advancements in materials science and technology, the widespread use of lightweight and highly durable new composite hoses in oil transportation has become increasingly prominent. These hoses demonstrate an elastic modulus significantly lower by at least two orders of magnitude compared to conventional steel pipelines. During the assessment of pipeline resistance, it is crucial to factor in the diameter variations caused by pressure increases to ensure a precise evaluation of the hydraulic friction in these composite hoses [1].

2 Hydraulic Design for Pumping Station Placement

The fundamental approach for the hydraulic design for locating pumping stations with liquid transfer lines is to plot the hydraulic grade line (HGL) on the longitudinal profile of the route in the same horizontal and vertical proportion to determine the location of the pumping stations. The application of hydraulic design for pumping station placement is to transform the graphical calculation approach into a specific coordinate system, expressing the relationships between points and points, points and lines, and lines and lines involved in the plotting process with equations or formulas. This mathematical approach describes the process of graphical calculation and graphical interpretation, thereby obtaining numerical results for the pumping stations. The particularity of the hydraulic design with hoselines lies in the significantly lower elastic modulus of hoses compared to steel pipelines. The considerable expansion and increase in hose diameter due to internal pressure result in varying hydraulic gradients along the line.

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In addition, the HGL is not a straight line but a curve with continuous curvature change [2]. Therefore, such particularity must be considered when determining and dealing with significant drops, calculating the number and average load of pumping stations, and defining the location of the pumping stations, in a bid to facilitate the design of an algorithm suitable for the application of pumping stations with hoselines.

Firstly, we establish a coordinate system, as shown in Figure 1. The route longitudinal profile features, HGL, pumping station/pressure reducing station (valve) locations, and inlet and outlet pressure heads can all be described using point coordinates and equations of lines (including straight segments and curves). The process of checking significant drops, determining peak turning points, and identifying the position of pumping stations can be completed through the determination of relationships between points and points, points and lines, and lines and lines in this coordinate system, as well as through related numerical calculations [3].

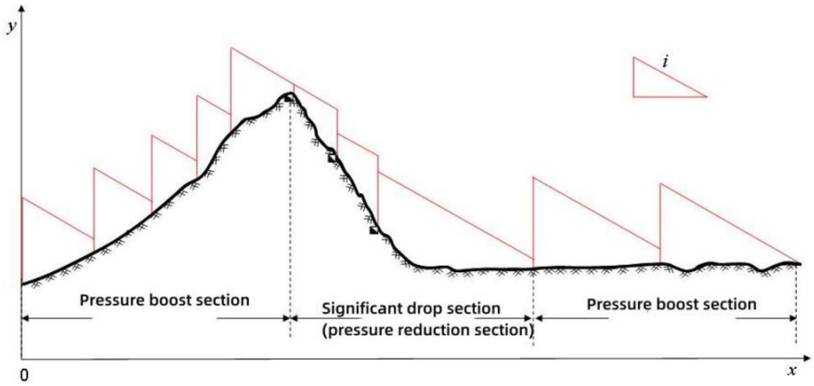

Figure 1 Coordinate System for Hydraulic Design with Hoseline

In the case of steel pipelines, the hydraulic gradient is constant, and the HGL is a straight line during design since the expansion of the pipes under internal pressure is insignificant. However, for hoselines with significantly lower elastic modulus compared to steel pipelines, the expansion and deformation under internal pressure must be taken into account. As a result, its hydraulic gradient varies with the changes in internal pressure and the position along the line, resulting in a curved HGL with continuous curvature change. The hydraulic friction of the hoseline is calculated using the following formula[4]:

$$h_f = \frac{B}{d_0} - \frac{B}{[(4-m)\Omega x + d_0^{4-m}]^{\frac{1}{4-m}}}$$

where

h_f is the hydraulic friction of the hose;

B is a comprehensive variable that characterizes the elasticity of the hose, and $B = \frac{2\delta E}{\rho g}$,

where

δ is the hose wall thickness,

E is the elastic modulus of the hose,

ρ is the liquid density,
g is the gravitational acceleration.
d_0 is the initial diameter of the hose (i.e., the diameter under no internal pressure).
m is the flow state index, with m = 1, 0.25, 0.123 and 0 corresponding to the laminar zone, hydraulically smooth zone, mixed friction zone, and resistance square zone, respectively.
x is the distance from the initial diameter to the base point where the dynamic pressure is 0, and Ω is a comprehensive variable that represents the resistance at the design flow, with $\Omega = \frac{\beta v^m q^{2-m}}{B}$,

where
β is the coefficient,
v is the liquid viscosity, and
q is the design flow.

(1) Determination and treatment of significant drops

Hoselines operate at relatively low pressures and are more prone to significant drops compared to steel pipelines under the same design flow and terrain conditions. The approach to identifying the existence of significant drops is illustrated in Figure 2:

1) To prevent negative pressure at high points in the line during pressure fluctuations, there should be a certain amount of residual pressure head at the high points. At point A, a high point in the line that may serve as the starting point of a significant drop, a vertical residual pressure head is measured upward at the same longitudinal proportion as the longitudinal profile, such as 10 m, leading to the establishment of point A'.

2) A HGL is drawn from point A', indicated by a dashed line ①, and its intersection M with the longitudinal profile is determined. The dynamic and static pressures between the high point and the intersection point are examined. If either pressure exceeds the limit, a significant drop exists; otherwise, there is no significant drop.

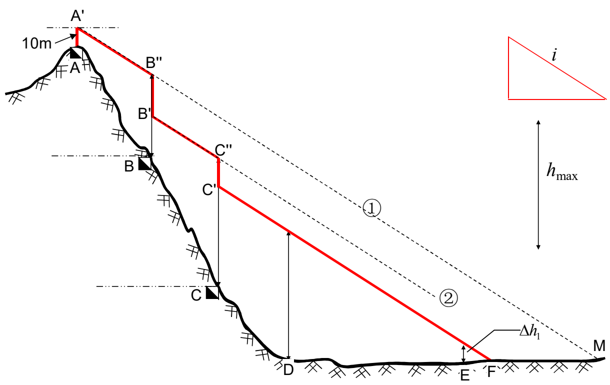

Figure 2: Determination and Treatment of Significant Drops

Measures such as setting up pressure reducing valves, thicker-walled pipes, or smaller-diameter pipes can be adopted for significant drops. For the hoselines, the suitable option is the installation of pressure reducing valves. The procedures are as follows[5]:

1) Locate the first pressure reducing valve at point A.

2) Between point A and intersection M, identify the points in sequence where the height difference with the currently installed pressure reducing valve is equal to the maximum allowable working pressure head of the hose, h_{max}. These points denote the locations of the second, third, and n-th pressure reducing valves, as shown at points B and C in Figure 2.

3) The setting of the outlet pressure head for each pressure reducing valve is based on the prerequisite that there is no occurrence of dynamic overpressure in the hose section from the valve outlet to the next pressure reducing valve inlet (or intersection M). To this end, assume that the pressure reducing valve does not require throttling reduction. Draw the HGL based on the inlet pressure head, as indicated by the dashed lines ① and ② in Figure 2. Next, determine whether there is dynamic overpressure downstream of the pressure reducing valve without throttling reduction. If there is dynamic overpressure (as shown at point D in Figure 2), the outlet pressure head of the pressure reducing valve needs to be reduced to eliminate overpressure downstream. If there is no dynamic overpressure, no throttling reduction is required. The outlet pressure head of the second pressure reducing valve in Figure 2 should be reduced from BB" to BB', and that of the third pressure reducing valve from CC" to CC'.

4) Following the dynamic pressure check and outlet pressure head adjustment, draw the HGL from the outlet of the last pressure reducing valve to intersect with the longitudinal profile of the route at point F. To ensure that the pumping stations in the succeeding pressure boost sections have positive inlet pressure heads, the endpoint of the significant drop section, i.e., the starting point of the succeeding pressure boost section, should be point E. The pressure head at point E is equal to the inlet pressure head of the first station, $\Delta h1$.

(2) Identification of peak turning points

The identification of the peak turning point is completed within a pressure boost section. A peak turning point is typically a high point near the end of the pressure boost section where the liquid must pass in order to be transported to the end of the section at the design flow rate. After the peak turning point, there might be a two-phase flow due to excess pressure energy, a slack flow that can be eliminated by measures such as throttling [4]. The approach to identifying peak turning points can be described as follows: Among the characteristic points in the longitudinal profile of the route within the pressure boost section, locate the point that requires the most pressure head to transport the liquid to that specific point. If that point is the actual endpoint of the pressure boost section, there is no peak turning point in this pressure boost section; otherwise, the point requiring the most pressure head is the peak turning point.

(3) Calculation of pumping station quantity and average load

Due to the variation in hose diameter along the line, the calculation of the number of pumping stations should be based on the working pressure head of a single pumping station under design conditions, using the following methods[6]:

1) Calculate the distance that the pumping station's working pressure head can transport,

$$l_P = \frac{\left(\frac{B\,\mathrm{d}_0}{B-\mathrm{d}_0 h_{sp}}\right)^{4-m} - \mathrm{d}_0{}^{4-m}}{(4-m)\Omega}$$

where h_{sp} is the lift that the pumping station can deliver under design conditions.

2) Calculate the number of pumping stations

$$n_C = \frac{L}{l_P} + \frac{\Delta z + \Delta h_z - \Delta h_1}{h_{sp}}$$

where L is the hose length within the pressure boost section. If there is a peak turning point in the boosting section, L is the calculated length; otherwise, it is the actual length of the hose. Δ_z is the delivery height. It is the calculated delivery height if there is a peak turning point; otherwise, it is the actual delivery height. Δh_z is the residual pressure head in the pressure boost section, and Δh_1 is the inlet pressure head at the starting point of the pressure boost section. The calculated number of pumping stations usually includes decimal points. To ensure the completion of the transport task and to reserve the potential for increased transport volume, the calculated number of pumping stations is rounded up to a larger integer n_R, which serves as the final number of pumping stations[7].

(3) Calculation of the average load of pumping stations

$$h_P = \frac{n_C h_{sp}}{n_R}$$

where h_p is the actual average load of pumping stations

(4) Pumping station arrangement

After calculating the required number of pumping stations for each pressure boost section and the actual average load h_p of each pumping station, the locations of the pumping stations within the pressure boost section are determined using graphical methods. The algorithm design involves the numerical description of the graphical process. Figure 3 shows the pumping station arrangement method proposed in the US Military Petroleum Pipeline Systems. The first station draws a HGL with h_p as the outlet pressure head (dashed line in Figure 3), and the intersection with the longitudinal profile of the route is the position of the second station. The second station draws a HGL with h_p as the outlet pressure head, and the intersection with the longitudinal profile of the route is the position of the third station. This process continues until all the pumping stations in the pressure boost section are arranged. If the HGL is a straight line, as in the case of steel pipelines [5], the inlet pressure head Δh_1 of the first station will be transmitted equally to the last station during actual pipeline operation (solid line in Figure 3). This method offers the advantage of not requiring the determination of an available arrangement area, providing a relatively fast process, and ensuring balanced loads with equal inlet and outlet pressure heads at each pumping station[8].

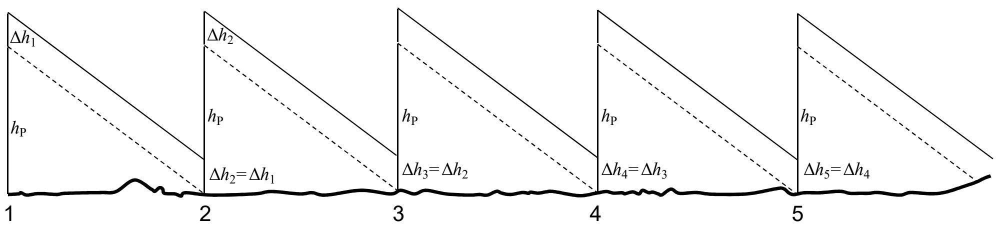

Figure 3 Equal Transmission of Inlet Pressure Heads at Each Station

However, when this method is used for hoselines, it cannot achieve equal transmission of inlet pressure heads at the first station. This is because the inlet pressure head of the second station exceeds that of the first station, followed by the third station's inlet pressure head exceeding that of the second station, and so on. Such a situation is caused by a reduction in hydraulic friction resulting from a further expansion of the hose due to the increased working pressure. The working pressure is higher because, when only the pumping station load is used to determine the location of pumping stations, the action of the inlet pressure head is taken into account after the hoseline is put into operation[9].

In this case, it is necessary to artificially ensure the equal transmission of the inlet pressure head from the first station to downstream pumping stations during the arrangement of the pumping stations. As shown in Figure 4, an HGL (curve) is drawn from the first station with an outlet pressure head of Δh_1+h_p to obtain its intersection point with the "longitudinal profile" (dashed line in Figure 4) higher than the route longitudinal profile by Δh. The longitudinal profile point corresponding to the intersection point is taken as the position of the second station. All pumping stations in the pressure boost section are arranged using this method. This is because for a hoseline, regardless of the number of pumping stations required, the same pump units are used for each pumping station, and the inlet pressure head requirement is consistent. As long as the inlet pressure head of the first station meets the requirement, the succeeding pumping stations will naturally meet the requirement as well. This method ensures the hydraulic state's consistency between the arranged and the actual operation, maintaining similar working loads and technical statuses for the pump units at each station. Adjustments to the pump load may be necessary if overpressure or underpressure points arise within a specific section, potentially resulting in changes to the pumping station positions.

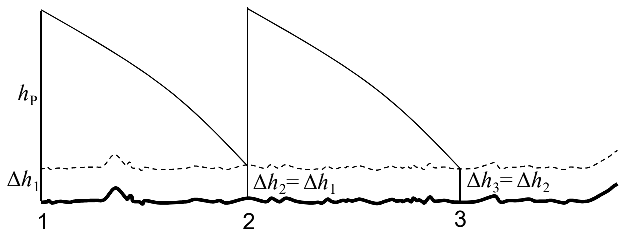

Figure 4 Hoseline Pumping Station Arrangement Method

3 Cross-station Transport Design

Cross-station transport refers to the process of passing a temporarily inactive pumping station during the transfer of liquid due to a power outage, accident, or maintenance to ensure continuous transportation of the liquid. The implementation of such transport typically requires adjustments. When pumping station C is shut down, the outlet pressure of station $c-1$ increases the most, while the inlet pressure of the station $c+1$ decreases the most, making the $c-1 \sim c+1$ segment the bottleneck for cross-station transport. The feasibility of cross-station transport needs to be determined through hydraulic calculations.

The conditions for safe and stable transport are as follows: the outlet pressure of each station should be lower than the hoseline's allowable maximum pressure, h_{max}, to avoid overpressure;

the inlet pressure should be higher than the pumping station's allowable minimum pressure, Δh_{min}, to avoid underpressure. If the $c-1 \sim c+1$ segment neither exceeds the maximum pressure nor falls below the minimum pressure, no adjustment is required to achieve cross-station transport. This situation is possible only when there is a considerable reserve of outlet pressure at station $c-1$ and inlet pressures at station $c+1$ before the shutdown of station C. In most cases, the reserves are insufficient, necessitating adjustment for cross-station transport.

The calculation method for adjusting the cross-station transport conditions is shown in Figure 5.

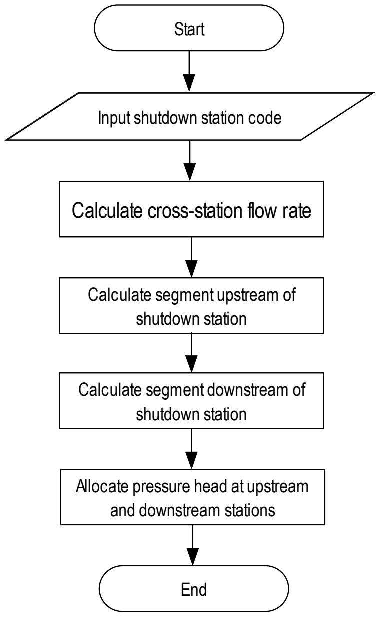

Figure 5 Flowchart of Cross-station Transport Calculation

(1) Calculation of cross-station flow rate

Firstly, the hoseline hydraulic status from the starting point to station $c+1$ without any adjustment is calculated. The inlet pressure head of station $c+1$ is set as Δh_{min}, and the pressure head balance equation is as follows:

$$\Delta h_1 + (c-1)H_{pump} = h_{f(c+1)} + \Delta z_{c+1} + \Delta h_{min} \quad (1)$$

$$H_{pump} = aq^2 + bq + w \quad (2)$$

where Δh_1 is the inlet pressure head of the first station;

H_{pump} is the pressure head provided by the transfer pump or booster pump, with a, b, and w as coefficients, and q as the flow rate;

$h_{f(c+1)}$ is the hydraulic friction loss from the starting point to station $c+1$;

Δz_{c+1} is the height difference between station $c+1$ and the starting point;

The simultaneous solution of Equations (1) and (2) yields the flow rate q through iterative methods.

By substituting q into Equation (3), the outlet pressure head of station $c-1$ is given by

$$\Delta h_{c-1} = \Delta h_1 + (c-1)H_{pump} - h_{f(c+1)} - \Delta z_{c-1} \qquad (3)$$

where $h_{f(c-1)}$ is the hydraulic friction from the starting point to station $c-1$;

Δz_{c-1} is the height difference between station $c-1$ and the starting point;

If $h_{c-1} < h_{max}$, cross-station transport can be achieved at this flow rate. If it is possible to add operating pump units or increase the rotational speed of the pump units to make h_{c-1} reach h_{max}, the cross-station flow rate can be increased to its maximum value, q^*_{max}.

If $h_{c-1} > h_{max}$, or although $h_{c-1} < h_{max}$, it is intended to raise h_{c-1} to h_{max}, then q^*_{max}, the maximum flow rate that can be achieved for cross-station transport, can be derived. For this purpose, the pressure balance equation between station $c-1$ and station $c+1$ can be expressed as follows:

$$\Delta h_{max} = (h_{f(c+1)} - h_{f(c-1)}) + (\Delta z_{c+1} - \Delta z_{c-1}) + \Delta h_{min}$$

Multiple iterations can approximate the value of the maximum cross-station flow rate, q^*_{max}.

(2) Calculation of section upstream of shutdown station

In cases where the calculated h_{c-1} according to the formula is greater or less than h_{max}, in order to maintain h_{c-1} at h_{max} while the flow rate is q^*_{max}, a head adjustment quantity h_s^* must be introduced. Its value can be determined from the head balance equation from the line's starting point to station $c-1$'s outlet:

$$\Delta h_1 + (c-1)H_{pump} = h_{f(c-1)} + \Delta z_{c-1} + h_{max} + h_s^*$$

This leads to:

$$h_s^* = \Delta h_1 + (c-1)H_{pump} - h_{f(c-1)} - \Delta z_{c-1} - h_{max}$$

(3) Calculation of section downstream of shutdown station

Let the pressure adjustment quantity for the downstream section be h_x^*. The head balance equation from station $c+1$ to the pipeline terminal is:

$$\Delta h_{min} + (n-c)H_{pump} = (h_{f(end)} - h_{f(c+1)}) + (\Delta z - \Delta z_{c-1}) + h_x^*$$

This leads to:

$$h_x^* = \Delta h_{min} + (n-c)H_{pump} - (h_{f(end)} - h_{f(c+1)}) - (\Delta z - \Delta z_{c+1})$$

where n is the number of pumping stations.

(4) Distribute the head adjustment quantities h_s^* and h_x^* equally among each pumping station to complete the cross-station transport calculation. The distribution calculation method for the upstream pumping station is as follows:

$$H_{si} = H_{pump} - \frac{h_s^*}{c-1}$$

$$H_{ins}[l] = hru$$

$$H_{outs}[i] = H_{ins}[i] + H_{si}$$

$$H_{ins}[i+1] = H_{outs}[i] - (h_{f(i+1)} - h_{f(i)})$$

where H_{si} is the pressure head provided by each upstream pumping station;

hru is the pressure head at the hoseline inlet;

$H_{outs}[i]$ is the outlet pressure head of the upstream pumping station i;

$H_{ins}[i]$ is the inlet pressure head of the upstream pumping station i;

Zi is the altitude of the pumping station i.

The distribution calculation method for the downstream pumping station is as follows:

$$H_{xi} = H_{pump} - \frac{h_s^*}{c-1}$$

$$H_{inx}[c+1] = \Delta h_{min}$$

$$H_{outx}[i] = H_{inx}[i] + H_{xi}$$

$$H_{inx}[i+1] = H_{outx}[i] - (h_{f(i+1)} - h_{f(i)})$$

where H_{xi} is the pressure head provided by each downstream pumping station;

$H_{outx}[i]$ is the outlet pressure head of the downstream pumping station *i*;

$H_{inx}[i]$ is the inlet pressure head of the downstream pumping station *i*;

The distribution methods for the upstream and downstream head adjustment quantities are relatively straightforward and can be obtained through iterative assignments.

4 Operational Parameter Adjustment Design

Parameter adjustment is the process of redistributing operational parameters based on actual measured operating parameters, following the principle of evenly distributing pressures among all stations. The main purpose of parameter adjustment is to ensure that the loads of each pumping station are roughly equivalent, the wear conditions are similar, and the technical states are mostly the same, which is beneficial for the long-term use of the hose system.

The distribution is based on accurate and reliable measurements, with the crucial condition being the absence of any peak turning points between stations. However, when the longitudinal profile of the hoseline lacks precision and fails to provide elevation data for a specific high point between stations, it might inadvertently lead to the emergence of such peak turning points. Consequently, the existence of these points can disrupt the normal oil transportation conditions in that section, emphasizing the need for their elimination. To eliminate the peak turning points between stations, the inlet pressure of the lower station can be increased to test the response of the upper station. If the outlet pressure of the upper station increases correspondingly, it indicates no peak turning point between the stations; otherwise, it signifies there is a peak turning point, and the inlet pressure of the lower station should be further increased until the presence of a response from the upper station. Since the measured data are all pressure gauge readings, for ease of use on the client side, the distribution method adopts pressure calculations, which can be converted to pressure heads in the end. The distribution method is as follows:

(1) Calculation of pressure needed for each station section

$$p_i^* = p_i' - \Delta p_{i+1}'$$

where p_i^* is the pressure needed for the section of station *i*;

p_i' is the measured outlet pressure of station *i*;

$\Delta p_{i+1}'$ is the measured inlet pressure of station *i*+1;

(2) Calculation of the average distributed pressure for each station:

$$\bar{p} = \frac{\sum_{i=1}^{n} p_i^* - \Delta p_1{}'}{n}$$

where $\bar{p}$ is the average distributed pressure for each station;

n is the number of pumping stations;

(3) Distribution of inlet and outlet pressures for each station

$$\Delta p_1 = \Delta p_1{}'$$

$$\Delta p_i = \Delta p_{i-1} + \bar{p} - p_{i-1}^* \text{ (Starting from i=2)}$$

$$p_i = \Delta p_i + \bar{p}$$

where Δp_i is the distributed inlet pressure for station *i*;

p_i is the distributed outlet pressure for station *i*.

5 Conclusions

This study focuses on the unique situation where the elastic modulus of the new composite polyurethane (PU) hose is at least two orders of magnitude lower than that of steel pipelines. In the calculation of hoseline resistance, the varying diameter of the hose is considered to accurately compute the hydraulic friction of the new composite hose. The corresponding mathematical model and hydraulic friction calculation formula are established. Furthermore, the study investigates the mathematical description method of the relationship between the HGL and the longitudinal profile of the route in a specific coordinate system when the HGL is a curve with continuous curvature change for the PU hose. In addition, for the case where the HGL line of the PU hose is a curve and its equation is nonlinear, numerical calculation methods are adopted to solve the coordinates of the pumping station location. We have transformed the corresponding mathematical model into a computer model, achieving the computerization of graphical and computational methods. In light of the PU hose, the study delves into the evolving pressure energy balance relationship under varying transport conditions, including changes in flow rate and cross-station delivery. It also studies an optimized operational plan that considers the impact of such factors as pump unit performance and hoseline dynamic pressure. This research introduces a fresh perspective on the hydraulic design of the oil transfer hoseline system, reinforcing the rationale behind pressure design in hoselines.

References

[1] Ke M. H. (2023). Exploration of hydraulic design optimization of shore spillway from the perspective of hydraulic model test [J]. Hydraulic Science and Technology, 178(01), 38-43.

[2] Cheng H. J., Wang Y. N., Xu J., et al. (2023). Influence of aeration wedge deflector design on hydraulic characteristics of spillway [J]. Mechanical and Electrical Technique of Hydropower Station, 46(02), 101-103. DOI:10.13599/j.cnki.11-5130.2023.02.028.

[3] [3] Tang, S. Z. (2022). Lubrication law and multi-objective optimization of high-pressure fuel pump bearings [D]. North University of China, DOI:10.27470/d.cnki.ghbgc.2022.000348.

[4] Wu L. (2023). Hydraulic design and calculation of steel dam gates [J]. Journal of Guangdong Polytechnic of Water Resources and Electric Engineering, 21(01), 1-4.

[5] Xie W. X., Zhang G. Z., Cheng J. Q., et al. (2022). Hydraulic design and numerical calculation of lean methanol pumps [J]. Pump Technology, 264(02), 1-5.

[6] Wang, Y. Study on Dynamic Characteristics and Anti-rollover Control of Liquid-filled Tractor-Semitrailer. Master Thesis, Nanjing Forest University, 2023. DOI:10.27242/d.cnki.gnjlu.2022.000219.

[7] Mir, Hafsa (AUTHOR)(hafsamir2@gmail.com);Abdul Hussain Ratlamwala, Tahir (AUTHOR)(tahir.ratlamwala@pnec.nust.edu.pk);Hussain, Ghulam (AUTHOR)(gh_ghumman@hotmail.com);Alkahtani, Mohammed (AUTHOR)(mabidi@ksu.edu.sa);Abidi, Mustufa Haider (AUTHOR).Impact of Sloshing on Fossil Fuel Loss during Transport.[J].Energies,2020,Vol.13(10): 2625

[8] Fatih C. Korkmaz.Wave impact on a rigid and flexible wall using various viscous fluids during sloshing[J].Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment,2023,Vol.237(1): 96-107

[9] Ibrahim, Raouf A..Assessment of breaking waves and liquid sloshing impact.[J].Nonlinear Dynamics,2020,Vol.100(3): 1837-1925