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Research on Operation Optimization of LNG Submerged Pump System in LNG Receiving Terminals

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Abstract: This paper focuses on improving the operating efficiency of the Liquified Natural Gas (LNG) submerged pump system in the LNG receiving terminals and achieve energy saving. The minimum input energy consumption of the LNG submerged pump system is taken as the objective function, and an optimization model for the operation of the LNG submerged pump system with variable frequency speed is established. LINGO18.0 optimization software is used to solve the model to get the optimal LNG submerged pump operation plan that satisfies the constraints. Taking a certain LNG receiving terminal as an example, the operation optimization of its LNG submerged pump system is carried out, and the input energy consumption of the system before and after optimization is compared. The results show that the use of variable frequency pumps can reduce the energy consumption of the LNG submerged pump system of LNG receiving terminals, and the optimization model can reduce the input power consumption of the system by about 10% under different transportation conditions. After applying the optimization model to actual production, it is found that the model has certain practicability for guiding the production of LNG receiving terminal.

Keywords: LNG receiving terminal; LNG submerged pump; operation optimization; energy saving

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1. Introduction

Since the Guangdong Dapeng LNG receiving terminal was put into operation in 2006, as of 2020, China has built 22 LNG receiving terminals, 9 LNG receiving terminals are under construction and 5 LNG receiving terminals have been expanded [1,2]. According to the International Gas Union (IGU) 2021 World LNG Report, as of 2020, 30 LNG receiving terminals are under construction. The LNG submerged pump is a main energy consuming equipment of LNG receiving terminal, LNG submerged pump system of the LNG receiving terminal is to pressurize the LNG in the LNG storage tank and transport it to the gasification unit through the LNG submerged pump. When LNG receiving terminals enter the stage of peak shaving or low transportation, the operating efficiency of the LNG submerged pump system is low, which leads to the high input energy consumption of the system. In order to realize energy saving and "Carbon Neutral" of LNG receiving terminal, this paper proposes to configure variable frequency LNG submerged pump in the system and conduct operation optimization research [3].

Domestic and foreign scholars have carried out a lot of research on the optimization of pump station operation, for the optimization problem of pumping station operation, scholars mostly use dynamic programming, intelligent algorithm and optimization software for research [4]. Zhuan et al. [5–7] used dynamic programming algorithm to study the operation optimization of a pumping station in the South-to-North Water Diversion Project to reduce the operating cost of the pumping station. Ercan et al. [8] used dynamic programming algorithm to optimize the control process of the heat pump system and proved through practice that the model can effectively reduce the energy consumption of the heat pump system. Zhang et al. [9] established an optimization mathematical model for the operation of the transportation oil pumping station based on the dynamic programming, the comparison of energy consumption before and after optimization shows that the optimization scheme provided by the model can effectively reduce energy consumption and operation cost. Feng et al. [10] introduced the Simulated Annealing (SA) algorithm into the Wolf Pack Algorithm (WPA) and named it the Hybrid Wolf Pack Algorithm (HWPA) for solving the pumping station optimization model. Meng et al. [11] used the Hybrid Genetic Algorithm (HGA) to optimize the operation of the variable frequency speed control pump, which reduces the operating cost of the pump station. Zhou et al. [12] used a hybrid algorithm combining Differential Evolution Algorithm (DEA) and Particle Swarm Optimization (PSO) to conduct operation optimization research on Heating Oil Pipeline (HOP), the optimization results show that the energy saving effect is significant. Chen et al. [13] used Non-dominated Sorted Genetic Algorithm-II (NSGA-II) to optimize the operation of the water supply pumping station and reduce the energy consumption of the water supply pumping station. Yuan et al. [14] established an optimal pump operation model which contained the constraint of start-stop pump unit, and used the Ant Colony Algorithm (ACA) to solve the optimization model, which reduces the operating cost of the pumping station. Wang et al. [15] used LINGO to optimize the water-supply pump station in small and medium cities. The dynamic programming method and the intelligent algorithm to solve the optimization model of the pump station have low stability and are more difficult to use than the optimization software, but the efficiency of finding the global optimal solution is high.

In this paper, a mathematical model for the operation optimization of the LNG submerged pump system including the general LNG submerged pump and the variable frequency LNG submerged pump is established, the optimization software LINGO18.0 is used to solve the optimal operation plan. Taking an LNG receiving terminal as an example, the adaptability study of the number of variable frequency LNG submerged pumps under different external delivery conditions has been performed. The optimal configuration scheme of variable frequency LNG submerged pumps is obtained. Under this scheme, the operation optimization of different external transportation flow rates of LNG submersible pump systems is carried out, and the optimal operation scheme of the system under different external transportation flow rates is obtained. The optimization model proposed in this paper has been tested in an LNG receiving terminal.

2. Methodology

2.1. LNG Submerged Pump Characteristic Curve Fitting

2.1.1. General LNG Submerged Pump

LNG submerged pumps are mostly electric centrifugal pumps. The centrifugal pump has its own characteristic curve when it runs at a certain speed. At present, the least squares method is commonly used to fit the characteristic curve of the centrifugal pump:

$$H = a_0 + a_1 q + a_2 q^2 \tag{1}$$

$$\eta = b_0 + b_1 q + b_2 q^2 \tag{2}$$

where H (m) is the head of the LNG submerged pump; η (%) is the pump efficiency of the LNG submerged pump; q (m^3/h) is the operating flow of the LNG submerged pump; and a_0, a_1, a_2, b_0, b_1 and b_2 are all undetermined values, which can be calculated according to the LNG submerged pump data provided by the manufacturer.

2.1.2. Variable Frequency LNG Submerged Pump

For the same pump, when the impeller diameter is unchanged and the same liquid is transported, and its rotational speed is changed, the relationship between the pump head, flow rate and shaft power obeys the Similarity Theory, and the relationship between the physical quantities is as follows:

$$\frac{q_1}{q_2} = \frac{n_1}{n_2} \tag{3}$$

$$\frac{H_1}{H_2} = \left(\frac{n_1}{n_2}\right)^2 \tag{4}$$

where q_1 and q_2 are the flow rates of the LNG submerged pump when the rotational speed is n_1 and n_2, respectively, H_1 and H_2 are the head of the LNG submerged pump when the speed is n_1 and n_2, respectively.

Assuming that the rated speed of the LNG submerged pump is n, the head H_{n1} and pump efficiency η_{n1} can be obtained when the speed of the variable frequency LNG submerged pump is n_1 according to the Similarity Theory:

$$H_{\mathrm{n}1} = a_0\left(\frac{n_1}{n}\right)^2 + \mathrm{a}_1 q\frac{n_1}{\mathrm{n}} + a_2 q^2 \tag{5}$$

$$\eta_{\mathrm{n}1} = b_0 + b_1 q + b_2\left(\frac{n}{n_1}q\right)^2 \tag{6}$$

2.2. Mathematical Models

2.2.1. Model Assumptions

In order to ensure the validity and accuracy of the mathematical model and avoid the influence of uncontrollable factors that may affect the actual operation of the LNG submersible pump, the following assumptions are made for the actual working conditions [9,16]:

1. Since the influence of variable frequency speed regulation on the performance of the LNG submerged pump motor is small, this influence is ignored;
2. Do not consider the impact of LNG submerged pump maintenance on the pump open plan;
3. During a period of operation, gas phase pressure and LNG density of the LNG storage tank remain unchanged, LNG tank level changes are negligible.

2.2.2. Objective Function

The minimum input energy consumption of the LNG submerged pump system is taken as the objective function. On the premise of satisfying the external transportation flow rate Qm (t/h) of the LNG receiving terminal and the process parameters of the LNG receiving terminal, the essence of the LNG submersible pump system operation optimization is to find the optimal pump opening scheme of the LNG submersible pump and the speed control ratio of variable frequency pump. The optimization objective function can be established as follows [17,18]:

$$\min F = \sum_{i=1}^{m} x_i N_i + \sum_{i=m+1}^{n} x_i N_i \tag{7}$$

where m is the number of general LNG submerged pumps; t is the total number of LNG submerged pumps in the LNG submerged pump system; F (kW) is the total input power of the LNG submerged pump system; N_i (kW) is the ith LNG submerged pump energy consumption; and x_i is the operating state of the ith LNG submerged pump (1 means that the LNG submerged pump is running, and 0 means that the LNG submerged pump is out of service).

2.2.3. Energy Consumption of LNG Submerged Pump

Most LNG submerged pumps are electric centrifugal pumps, and when the motor is running, there is power loss. However, the converter of the variable frequency LNG submerged pump also has power loss. The power loss of the general LNG submerged pump and the variable frequency LNG submerged pump is shown in Figures 1 and 2, respectively.

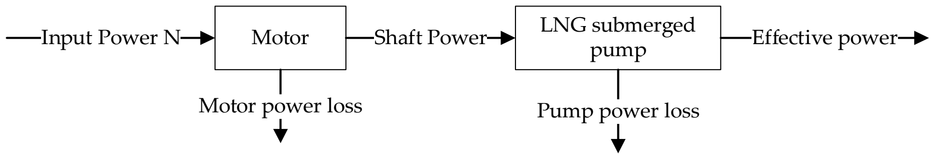


Figure 1. Power loss diagram of general LNG submerged pump.

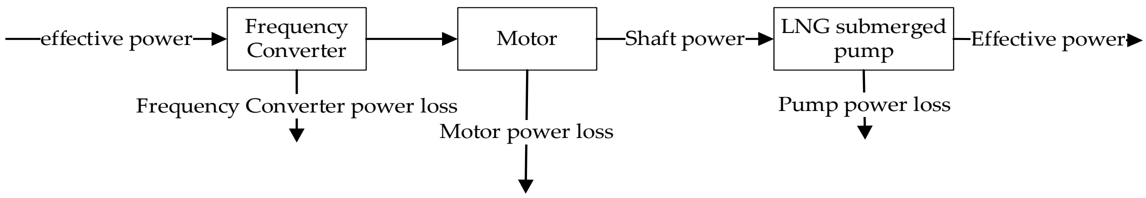


Figure 2. Power loss diagram of variable frequency LNG submerged pump.

According to Figure 1, the input power of the general LNG submerged pump can be obtained.

$$N = \frac{\rho g q H(q)}{360\eta_{motor}\eta(q)} \tag{8}$$

According to Figure 2, the input power of the variable frequency LNG submerged pump can be obtained.

$$N = \frac{\rho g q H_{\mathrm{n1}}(q)}{3.6\eta_{converter}\eta_{motor}\eta_{\mathrm{n1}}(q)} \tag{9}$$

$\eta_{converter}$ (%) is the converter efficiency. The calculation equation is as follows [19]:

$$\eta_{\mathrm{converter}} = 50.87 + 128.3\frac{n_1}{n} - 142\left(\frac{n_1}{n}\right)^2 + 58.34\left(\frac{n_1}{n}\right)^3 \tag{10}$$

After considering the power loss of the motor and the frequency converter, the objective function of the operation optimization of the LNG submerged pump system becomes:

$$\min F = \sum_{i=1}^{m} x_i \frac{\rho g q H(q_i)}{360\eta_{motor}\eta(q_i)} + \sum_{i=m+1}^{n} x_i \frac{\rho g q H_{\mathrm{ni}}(q_i)}{3.6\eta_{\mathrm{converter}}\eta_{motor}\eta_{\mathrm{ni}}(q_i)} \tag{11}$$

among them ρ (kg/m^3) is the density of LNG; g (m/s^2) is the acceleration of gravity, generally 9.8m/s^2; qi (m^3/h) is the operating flow of the ith LNG submerged pump; and η_{mot} (%) is the driving motor efficiency of the LNG submerged pump.

2.2.4. Restrictions

- Hydraulic constraints

In order to meet the daily production process requirements of the LNG receiving terminal, it is necessary to limit the outlet pressure of the operating LNG submerged pump.

$$x_i P_{\min} \le x_i P_i \le x_i P_{\max} \tag{12}$$

$$P_i = \frac{\rho g[L + H(q_i)]}{1000} + P_{\tan k} \tag{13}$$

where P_i (kPa) is the outlet pressure of the ith pump (xi=1); L (m) is the liquid level of the LNG storage tank; and P_{tank} (kPa) is the gas space pressure of the LNG storage tank.

- Running flow constraints

The LNG submerged pump used in the LNG receiving terminal is generally a centrifugal pump, which needs to meet the flow constraints of its flow adjustment range:

$$x_i q_{\min} \leq x_i q_i \leq x_i q_{\max} \tag{14}$$

- External transportation flow constraints

In the LNG receiving terminal, the LNG submerged pump system must meet the requirements of the external transportation of the LNG receiving terminal.

$$Q_m = \sum_i \frac{\rho q_i}{1000} \tag{15}$$

where Q_m (t/h) is the external LNG demand transportation flow rate.

- Variable frequency speed regulation constraints

The operating speed of the variable frequency LNG submerged pump needs to meet:

$$n_{\min} \leq n_i \leq n \tag{16}$$

where n_{min} (r/min) is the minimum speed, r/min and n (r/min) is the rated speed.

3. Model Solving

The operation optimization model of the LNG submerged pump system is a MINLP (Mixed Integer Non-linear Programming) optimization problem, which is difficult to solve directly. LINGO software is an optimization software that solves the global optimal solution of the MINLP problem based on the branch-and-cut method. Once the global optimal solution takes too long to solve, the built-in heuristic algorithm is used to solve the NLP (Non-linear Programming) sub-problems decomposed by MINLP. LINGO is mostly used in solving multi-objective NLP, but LINGO can also be used for single-objective NLP. For example, Zhu et al. [20] took the minimum cost of shear wall structure as objective function, used LINGO to optimize the shear wall structure. Wang et al. [15] took the minimum operating cost of the pumping station as the objective function, and used LINGO to optimize the operation of the water supply pumping station.

For the hydraulic constraints in the operation optimization model of the LNG submerged pump system of the LNG receiving terminal, the penalty function f is constructed to solve the problem [21].

$$f = \left(\sum_{i=1}^{n} |\mathrm{x}_i P_i - 1200\mathrm{x}_i| \right)^2 \tag{17}$$

after adding the hydraulic constraint f, the final form of the objective function is:

$$\min F_{\mathrm{ct}} = F + cf \tag{18}$$

where F is the objective function of the operation optimization model of the LNG submerged pump system and c is the penalty of hydraulic constraints.

4. Case Study

4.1. Boundary Conditions

The process flow of the LNG submerged pump system in the LNG receiving terminal is shown in Figure 3, an LNG receiving terminal has 4 LNG storage tanks, and each LNG storage tank is equipped with 3 LNG submerged pumps, a total of 12 LNG submerged pumps with the same performance. The 12 LNG submerged pumps are all 60723L2-R185F cryogenic pumps from *NIKKISO*. This type of cryogenic pump has an operating flow range of 140 ~427 m^3/h and its rated speed is 3000 r/min. LNG submerged pump performance is shown in Figure 4.

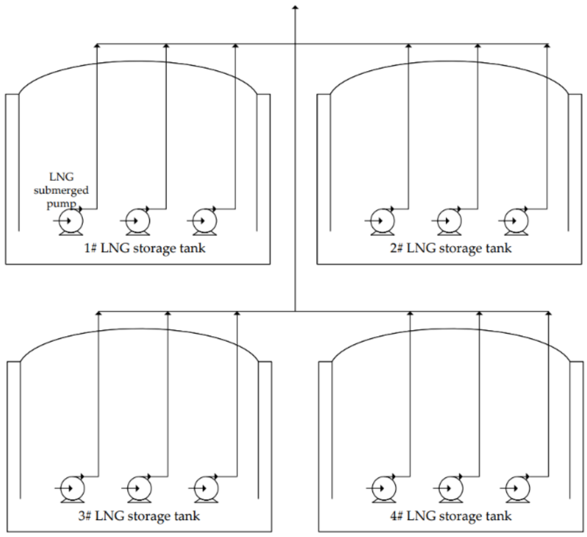
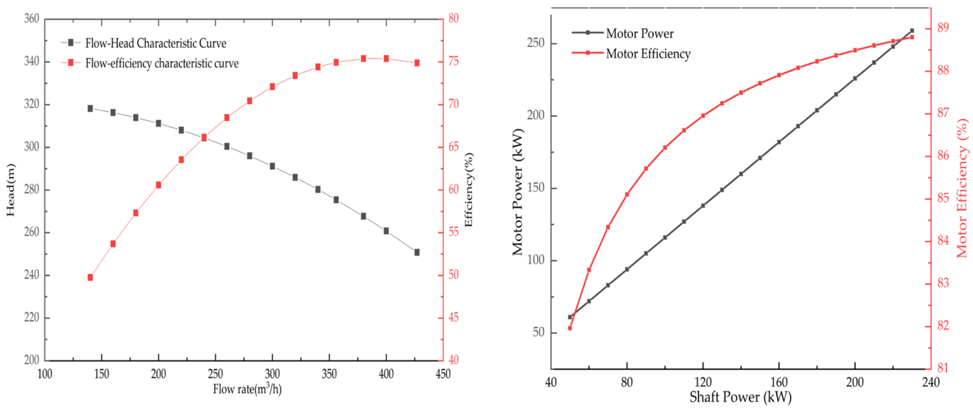


Figure 3. LNG submerged pump system process flow chart.



(**a**) (**b**)

Figure 4. LNG submerged pump performance: (**a**) LNG submerged pump characteristic curve; (**b**) LNG submerged pump motor performance curve.

The relationship q-H (flow-head) and q-η (flow-efficiency) of the LNG submerged pump is as follows:

$$H = -0.00052q^2 + 0.06q + 320 \tag{19}$$

$$\eta = -0.00041q^2 + 0.32q + 13 \tag{20}$$

The relationship between the shaft power and the motor power of the LNG submerged pump is:

$$P_{Motor\ power} = 1.1P_{Shaft\ power} + 6 \tag{21}$$

where $P_{Motor\ power}$ (kW) is the LNG submerged pump motor power and $P_{Shaft\ power}$ (kW) is the LNG submerged pump shaft power.

The operating range of the process parameters of the LNG submerged pump system of an LNG receiving terminal is shown in Table 1. According to the similarity theory and the characteristic curve of the general LNG submerged pump, the performance calculation of the variable frequency pump and the drawing of the characteristic curve are carried out. In the calculation, the speed adjustment of the variable frequency LNG submerged pump is divided into seven categories, namely 3000 r/min, 2900 r/min, 2800 r/min, 2700 r/min, 2600 r/min, 250 r/min and 2400 r/min. After the calculation, the characteristic curve of the variable frequency LNG submersible pump is shown in Figure 5.

Table 1. Constraints of the LNG submerged pump system in an LNG receiving terminal.

Process Parameter	Boundary Conditions
LNG storage tank pressure P_{tank} (kPa)	15~22
LNG storage tank level L (m)	2.4~33.5
LNG submerged pump outlet pressure P (kPa)	1150~1350

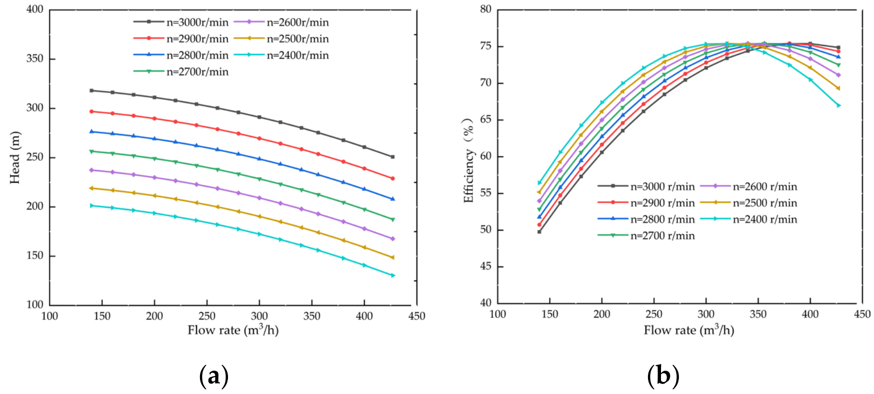


Figure 5. Characteristic curve of the variable frequency LNG submerged pump at different speeds: (**a**) q-H; (**b**) q-η.

According to the above model assumptions and the production data of a certain LNG receiving terminal, the pressure of the LNG storage tank of a certain LNG receiving terminal does not change much, so the pressure of the LNG storage tank is assumed to be 20 kPa. According to the LNG source composition parameters of a certain LNG receiving terminal, the LNG density is assumed to be 436.6 kg/m^3.

4.2. Operation Optimization of LNG Submerged Pump System

4.2.1. Operation Optimization based on Historical Production Data

Under the current LNG submerged pump configuration scheme of an LNG receiving terminal, the operation scheme is optimized for a certain external transportation condition. According to the mathematical model built above, LINGO18.0 is used to solve the problem. The optimization results of the operation scheme of the LNG submerged pump system are shown in Table 2.

Table 2. Optimization results of the operation plan under the current LNG submerged pump configuration plan of an LNG receiving terminal.

Submerged Pump Number	q (m^3/h)		η (%)		N (kW)	
	Before Optimization	Optimized	Before Optimization	Optimized	Before Optimization	Optimized
1	~	~	~	~	~	~
2	~	~	~	~	~	~
3	263.17	237.07	68.82	65.82	155.87	149.62
4	254.70	~	67.91	~	153.87	
5	307.38	393.13	72.62	75.44	166.09	185.34
6	~	273.07	~	65.82	~	149.62
7	~	~	~	~	~	
8	269.35	~	69.45	~	157.33	
9	~	~	~	~	~	
10	269.35	~	69.45	~	157.33	
11	~	393.13	~	75.44	~	185.34
12	270.96	393.13	69.61	75.44	157.70	185.34
Total	1634.91	1653.53	~	~	948.19	855.26

According to Table 2, it can be found that the model can greatly reduce the input energy consumption of the LNG submerged pump system and improve the operating efficiency of the LNG submerged pump. However, it is found that the operating efficiency of some LNG submerged pumps is still low, this is due to the limitation of the external transportation flow rate of the LNG receiving terminal. In view of this situation, the use of variable frequency LNG submerged pumps is proposed, and then the adaptability of the number of variable frequency LNG submerged pumps in a certain LNG receiving terminal under different external transport conditions is studied. Figure 6 shows the survey results of the LNG external transportation flow rate of an LNG receiving terminal in 2020, and finds that the external transportation flow rate of an LNG receiving terminal fluctuates between 560 t/h and 1120 t/h. The adaptability study of the number of variable frequency LNG submerged pumps under different external delivery conditions has been performed. The number of variable frequency pumps installed in the LNG submerged pump system is optimized, and the research results are shown in Figure 7.

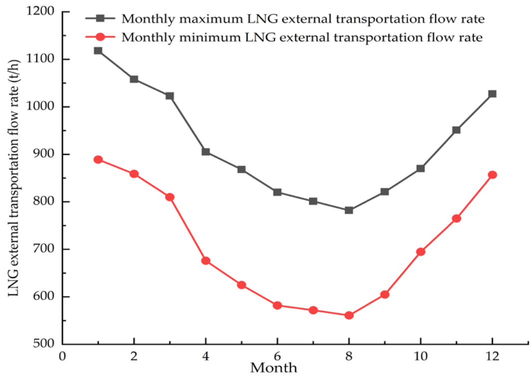


Figure 6. LNG external transportation flow rate of an LNG receiving terminal in 2020.

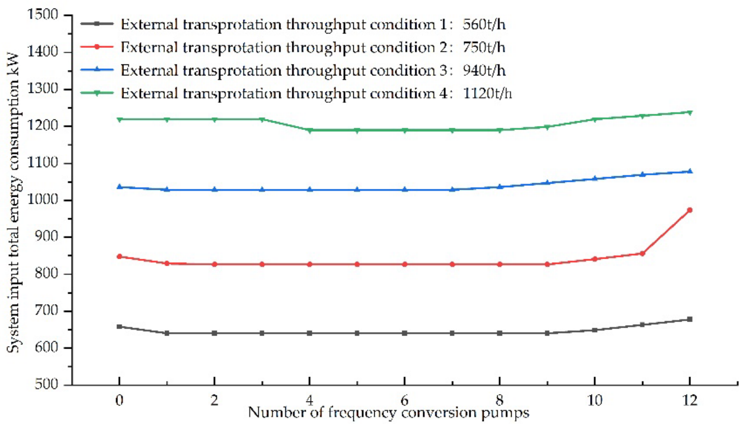


Figure 7. The adaptability study results of the number of variable frequency LNG submerged pumps under different external delivery conditions.

It can be found from Figure 7 that:

Under different external transportation flow, with the increase in the number of variable frequency LNG submerged pumps, the total input energy consumption of the LNG submerged pump system always shows a trend of first decreasing, then leveling off and finally increasing. This shows that the use of variable frequency LNG submerged pumps can reduce the total input energy consumption of the LNG submerged pump system and improve the operating efficiency of the system. However, with the increase in the number of variable frequency LNG submerged pumps, some high-efficiency general LNG submerged pumps stop running, it is necessary to start multiple frequency conversion pumps to meet the external transportation task. Due to the power loss of the frequency converter, the total input energy consumption of the system increases and the system operation efficiency decreases.

To sum up, there is an optimal LNG submerged pump configuration scheme for an LNG receiving terminal, so that the LNG submerged pump system can operate with the lowest total energy consumption of the system input under different external transportation flow. When the external transportation flow of the LNG submerged pump system is: 560 t/h, 750 t/h, 940 t/h and 1120 t/h, respectively, set up 1, 2, 1 and 4 variable frequency LNG submerged pump, the system input power consumption and equipment (frequency converter) investment are both the smallest. Therefore, the LNG submerged pump system of an LNG receiving terminal should be equipped with four variable frequency LNG submerged pumps, so that the LNG submerged pump system can operate according to the optimal operation plan under different external transportation conditions.

When four variable frequency LNG submerged pumps are installed in the LNG submerged pump system of an LNG receiving terminal, LINGO18.0 is used to solve the problem according to the established mathematical model. According to the on-site production data of an LNG receiving terminal, four external transportation flow rate conditions are selected. The operation optimization of the LNG submerged pump system is carried out, in which Nos. 1–8 are power frequency LNG submerged pumps, and 9–12 are variable frequency LNG submerged pumps. The optimization results are shown in Table 3. The energy consumption comparison before and after optimization of the LNG submerged pump system of an LNG receiving terminal is shown in Table 4.

Table 3. Optimized operation plan of LNG submerged pump system under different external transportation flow.

Submerged Pump Number	Q_m: 713 t/h		Q_m: 843 t/h		Q_m: 1047 t/h		Q_m: 1133 t/h	
	n (r/min)	q (m^3/h)	n (r/min)	q (m^3/h)	n (r/min)	q (m^3/h)	n (r/min)	q (m^3/h)
1	3000	371.6	3000	371.7	3000	374.0	3000	370.6
2	3000	371.6	3000	371.7	3000	374.0	3000	370.6
3	~	~	~	~	3000	374.0	3000	370.6
4	~	~	~	~	3000	374.0	3000	370.6
5	~	~	~	~	~	~	3000	370.6
6	~	~	~	~	~	~	3000	370.6
7	~	~	~	~	~	~	~	~
8	~	~	~	~	~	~	~	~
9	~	~	2900	296.8	~	~	~	~
10	2900	296.6	2900	296.8	2900	300.6	~	~
11	2900	296.6	2900	296.8	2900	300.6	2800	185.5
12	2900	296.6	2900	296.8	2900	300.6	2800	185.5

Table 4. Comparison of optimized operation power consumption of LNG submerged pump system.

Q_m (t/h)	Operating Plan			F (kW)		Operating Efficiency (%)		Energy Saving (%)
	Before Optimization	Optimized		Before Optimization	Optimized	Before Optimization	Optimized	
	g	v	g					
713	6	3	2	919.8	818.2	62.82	64.16	11.05
843	7	4	2	1079.0	970.6	62.53	63.93	10.05
1047	9	3	4	1362.3	1172.0	62.62	65.56	13.97
1133	9	2	6	1417.3	1289.0	61.85	63.25	9.05

g: Number of general LNG submerged pumps in operation; v: Number of variable frequency LNG submerged pumps in operation.

According to Table 4, it can be found that before and after optimization, when the external transportation flow is 704 t/h, 832 t/h, 1034 t/h and 1119 t/h, respectively, the energy saving effect of system input power consumption is 11.05%, 10.05%, 13.97% and

9.05%, respectively, and the operating efficiency of the LNG submerged pump system is slightly improved. This is because the converter in the variable frequency LNG submerged pump has energy loss, which increases the input side energy consumption of the variable frequency LNG submerged pump unit. To sum up, after the LNG submerged pump system of the LNG receiving terminal adopts the variable frequency LNG submerged pump, the input energy consumption of the LNG submerged pump system can be reduced.

4.2.2. On-Site Production Application of LNG Receiving Terminal

The above studies are all based on the historical production data of an LNG receiving terminal to optimize the operation of the LNG submerged pump system. Now the optimization model and the optimal configuration scheme of the LNG submerged pump are applied to the actual production on site. According to the production plan of an LNG receiving terminal in April 2022, the LNG external transportation flow rate on a certain day is about 820 t/h. First, the optimization model is used to determine the operation plan of the LNG submersible pump system, and then the optimized operation plan is applied to the actual production. Compare the actual production data with the on-site production data with the same LNG export volume in this month, as shown in Table 5.

Table 5. Model optimization and field application results.

Submerged Pump Number	q (m^3/h)			n (r/min)		N (kW)		
	Optimized	Applied	Historical	Optimized	Applied	Optimized	Applied	Historical
1	372.34	356.23	~	3000	3000	158.66	155.53	~
2	372.34	361.93	265.28	3000	3000	158.66	156.69	156.37
3	~	~	243.56	~	~	~	~	151.20
4	372.34	352.98	~	3000	3000	158.66	154.87	~
5	~	~	~	~	~	~	~	~
6	372.34	351.59	257.98	3000	3000	158.66	154.59	154.65
7	~	~	241.18	~	~	~	~	150.62
8	~	~	250.13	~	~	~	~	152.78
9	194.40	189.35	~	2800	2800	100.74	99.81	~
10	194.40	186.29	272.58	2800	2800	100.74	99.17	158.08
11	~	~	~	~	~	~	~	~
12	~	~	268.07	~	~	~	~	157.03
Total	1878.15	1798.37	1798.78	~	~	969.02	951.84	1080.723

According to Table 5, it can be found that:

According to the comparison between the model application results and the previous production data of the same LNG export condition. It can be found that the application of the optimized model can significantly reduce the input power consumption of the LNG submerged pump system, the input power consumption is reduced by about 130 kW and the system operation efficiency is improved. Therefore, the optimization model proposed in this paper has certain practicability and effectiveness and can guide the production operation of the LNG receiving terminal. However, there is a certain gap between the model optimization results and the application results, especially the flow rate of the LNG submerged pump. This may be due to the long-term service of the LNG submersible pump, resulting in a decrease in its performance, or a change in the physical properties of the LNG. In the follow-up, the actual performance of the LNG submerged pump will be evaluated according to the on-site situation of the LNG receiving terminal, and the optimization model proposed in this paper will be modified to make it more in line with the actual situation of on-site production.

5. Conclusions

In this paper, an operation optimization model of the LNG submerged pump system is established, and the LINGO18.0 optimization software is used to solve the optimal operation plan. Taking an LNG receiving terminal as an example, the operation plan is optimized, and it is found that the model can reduce the input energy consumption of the LNG submerged pump system and improve the operating efficiency of the LNG submerged pump. According to the adaptability research results of the number of variable frequency LNG submerged pumps under different external transmission conditions, it is found that the variable frequency LNG submerged pump can reduce the input energy consumption of the system. The optimal LNG submerged pump configuration scheme is determined: four variable frequency pumps and eight general pumps. With this scheme it was found the input power consumption of the LNG submerged pump system can be reduced by about 10% under different transportation conditions of the considered LNG receiving terminal. Through the practical application of the optimization model, it is found that the optimization model proposed in this paper can guide the production operation of the LNG receiving terminal, reduce the production energy consumption of the LNG terminal and realize the "carbon neutrality" of the LNG receiving terminal. However, the matching degree of this model with the actual situation on site is not very high, and follow-up research will continue to make the model more suitable for the actual situation of the LNG receiving terminal.

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