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Hydraulic model optimization of a multi-product pipeline

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Abstract: An optimization model is established for a multi-product pipeline which has a known delivery demand and operation plan for each off-take station. The aim of this optimization model is to minimize the total pumping operation cost, considering not only factors including the energy equilibrium constraint, the maximum and minimum suction and discharge pressures constraints of pump stations, and pressure constraint at special elevation points, but also the regional differences in electricity prices along the pipeline. The dynamic programming method is applied to solve the model and to find the optimal pump configuration.

Key words: Multi-product pipeline, pump sets, regional electricity price, optimization, dynamic programming

1 Introduction

Products of different physical properties, such as diesel and various gasolines, transported in the same pipeline, result in the pressure characteristics along the pipeline being more complicated than that of a single product pipeline (Gong and Yu, 1992; Rejowski and Pinto, 2004; Tang et al, 2011). The greatest feature of a multi-product pipeline is batch transportation. Variations in the pump station characteristics and pipeline characteristics caused by batch movement of different products in the pipeline, and delivery/injection operations along the pipeline result in changes of the configuration of pump sets of the whole pipeline. Different configurations of pump sets impose diverse pipeline operation costs. Many studies have been performed on power cost optimization, especially concerning optimizing configurations of pump sets to achieve minimum pumping power cost while ensuring operation safety and satisfying the delivery requirements. The optimal pump configuration in previous studies has been mainly determined by considering constraint conditions such as maximum and minimum suction and discharge pressures, pressures of high-elevation points, and speed range of the control motor, with a constant electricity price assumption (Liang, 2004). In China, a multi-product pipeline usually crosses many areas. Because of the long distances, regional electricity prices may be considerably different owing to various electricity generating costs. Therefore, the assumption of a constant electricity price is not suitable for Chinese domestic conditions. So it is necessary to establish an optimization model for pipeline operations in which the regional differences in electricity prices are taken into account.

The pipeline operators press for effective off-line simulation software for optimizing multi-product pipeline operations. SCICLOPS from Britain, PACOS developed by the Pichler company in German and SPS by the STONER company in America are widely used in the pipeline simulation field, but no standardized software for multi-product pipeline simulation developed in China. On the basis of optimization theory, a mathematical model for optimizing operations of multi-product pipeline has been developed using dynamic programming. The software STROBER for multi-product pipeline operation simulation has been developed.

2 Target function of the model

The optimal configuration of pumps and the minimum throttling volume in pump stations can be calculated in order to minimize total electricity cost and to ensure the most efficient and economic operation of a multi-product pipeline. A multi-product pipeline system can be modeled using an energy conservation equation. This equation must meet the following constraints: The flow rate through the initial pump station should be as stable as possible over a long period. The inlet and outlet pressures of pump stations and pressures of some special points should be within the preset limits and the delivery task should be completed during the prescribed time (Liang et al, 2004; Rejowski and Pinto, 2003; Méndez and Cerdá, 2003). The target function of this model is given by:

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$$\min F=\sum_{j=1}^{JN}\sum_{i=1}^{IN}\sum_{u=1}^{UN_i}\frac{W_{i,u}^{j}S_i\rho_i^j gQ_i^j\left(A_{i,u}\dfrac{\left(n_{i,u}^{j}\right)^2}{\left(n_{i,u}^{r}\right)^2}+B_{i,u}\left(Q_i^j\right)^{7/4}\right)}{3.6\times10^{6}\times\left(a_{i,u}\dfrac{\left(n_{i,u}^{j}\right)^2}{\left(n_{i,u}^{r}\right)^2}\left(Q_i^j\right)^2+b_{i,u}\dfrac{n_{i,u}^{j}}{n_{i,u}^{r}}Q_i^j+c_{i,u}\right)}\Delta t_j \tag{1}$$

3 Model constraints

3.1 Energy use along the pipeline

$$P_{\mathrm{s}}^{j}+\sum_{i=1}^{IN}\sum_{u=1}^{UN_i}H_{i,u}^{j}\rho_i^j g=F_{\mathrm{h}}^{j}+V_{\mathrm{cut}}^{j}+P_{\mathrm{e}}^{j}+L_1+F^{j} \tag{2}$$

The above equation represents energy use of the multi-product pipeline system at the *j*th time step. In a multi-product pipeline system, the pump sets are connected in series. The equation will be modified correspondingly when the pump sets are connected in parallel.

3.2 Pressure constraints at special points

These special points refer to some points at low and high elevations along the pipeline. Super-high pressure at the lowest elevation point and vaporization at the highest elevation point may occur. To avoid these extremes, the pressure constraints for these special points are as below:

$$P_{\mathrm{spe\_min}}^{g}\le P_{g,\mathrm{spe}}^{j}\le P_{\mathrm{spe\_max}}^{g} \tag{3}$$

3.3 Discharge pressure constraint

Considering the pressure bearing capacity of the pipeline and associated downstream equipment, the discharge pressure should meet the following constraint at the *j*th time step:

$$P_{i,\mathrm{d}}^{j}\le P_{i,\mathrm{d\,max}}^{j} \tag{4}$$

In this equation, the preset constraint of the discharge pressure should be given at each time step under different conditions.

3.4 Suction pressure constraint

In order to consider the allowable bearing pressure of the pump station equipment and the allowable suction pressure, the suction pressure should meet the following constraint at the *j*th time step:

$$P_{i,\mathrm{s\,min}}^{j}\le P_{i,\mathrm{s}}^{j}\le P_{i,\mathrm{s\,max}}^{j} \tag{5}$$

In the equation, the preset constraint of the maximum and minimum suction pressures should be given at each time step.

3.5 Delivery task constraint

The end of a transport cycle can be described as:

$$V=\sum_{j=1}^{JN}Q_1^j\Delta t_j \tag{6}$$

3.6 Maximum delivery capacity constraint

Ignoring the temperature variation of fluids, the maximum delivery capacity of a single-fluid pipeline is constant over a long period. However, for a long-distance pipeline having several pump stations, the suction and discharge pressures of each pump station, together with the pressures at special points, vary with transport time due to fluid flow and variation of the product batches in the pipeline. In addition, the pressure variation in the pipeline, caused by start-up and shut-down of the off-take stations along the pipeline, results in a change in the maximum delivery capacity of the pipeline (Cafaro and Cerdá, 2004; Hui and Gupta, 2000; Hui et al, 2000).

When multiple products or batches are transported in a pipeline, the maximum delivery capacity of the pipeline should be constantly determined to maximize pipeline utilization. The maximum delivery capacity can be calculated with methods proposed by other researchers (Prasad and Maravelias, 2008; Cafaro and Cerdá, 2008; 2010). The input flow rate of the initial station must meet the constraint as indicated below:

$$Q_1^j\le Q_{\max}^j \tag{7}$$

4 Model analysis

The aim of this model is to minimize the electricity cost of pump stations. Therefore, the optimal operation scheme is that one which can most effectively minimize the electricity cost in the operation cycle.

To obtain the optimization result of pump sets, work can be divided into several procedures. Each stage is likely to have different decisions. Therefore, this optimization is a multi-stage decision problem. The most commonly used method to solve multi-stage decision problems is dynamic programming theory. The main idea of dynamic programming theory is the "optimization principle", namely, for a multi-stage decision process – whatever their front process strategies are – the optimal strategy depends only on the current state. Based on this theory, many researchers have proposed a series of solutions.

For each interval between stations, the problem of pipeline pressure distribution can be divided into several phases. Assuming that the problem is divided into n phases and x_p represents the start of the *p*th phase, x_p ($1\le p\le n$) represents the state variables of each state. Variable sets of each state are described as $x_p=\left\{x_p^1,x_p^2,\cdots,x_p^n\right\}$. The decision variable of the *p*th state is the effective pressure head provided by the *p*th pump station, namely $u_p=\sum_{u=1}^{UN_p}\left(H_{p,u}^{j}\times W_{p,u}^{j}\right)$. The allowable decision set can be described as $U_p\left(x_p\right)$. The state transfer equation can be described as $x_{p+1}=x_p+u_p$.

Constraint conditions: State variables x_{p} in the model meet a series of constraints: the maximum and minimum pressure constraints at special points along the pipeline and the maximum and minimum suction/discharge pressure constraints of each pump station:

$$A_p^j \le x_p \le B_p^j \tag{8}$$

$$A_p^j = \max(A1_p^j, A2_p^j) \tag{9}$$

$$B_p^j = \min(B1_p^j, B2_p^j, B3_p^j) \tag{10}$$

Minimum suction pressure constraint:

$$\mathrm{A}1_p^j = P_{p+1,\mathrm{s}\min}^j - P_{\mathrm{s}}^j + F_{p+1}^j + F_{\mathrm{h},p+1}^j + L_{1,p+1} + V_{\mathrm{cut},p+1}^j \tag{11}$$

Pressure constraint of higher points of elevation:

$$\mathrm{A}2_p^j = P_{\mathrm{spe\_min},p+1} - P_{\mathrm{s}}^j + \overline{F_{p+1}^j} + \overline{F_{\mathrm{h},p+1}^j} + L_{1,p+1} + V_{\mathrm{cut},p+1}^j \tag{12}$$

Maximum suction pressure constraint:

$$B1_p^j = P_{p+1,\mathrm{s}\max}^j - P_{\mathrm{s}}^j + F_{p+1}^j + F_{\mathrm{h},p+1}^j + L_{1,p+1} + V_{\mathrm{cut},p+1}^j \tag{13}$$

Maximum discharge pressure constraint:

$$B2_p^j = P_{p,\mathrm{d}\max}^j - P_{\mathrm{s}}^j + F_p^j + F_{\mathrm{h},p}^j + L_{1,p+1} + V_{\mathrm{cut},p+1}^j \tag{14}$$

Pressure constraint of lower points of elevation:

$$B3_p^j = P_{\mathrm{spe\_max},p+1} - P_{\mathrm{s}}^j + \overline{F_{p+1}^j} + \overline{F_{\mathrm{h},p+1}^j} + L_{1,p+1} + V_{\mathrm{cut},p+1}^j \tag{15}$$

5 Model solution

The optimization of a multi-product pipeline is different from that of a crude oil pipeline or a natural gas pipeline. Hydraulic conditions along the pipeline change owing to fluid flow and variation of product batches, and frequent start/stop operations of each distribution station. Therefore, pump optimization is required for the entire simulation process.

In order to reduce the memory size required for the calculation and to increase the computational speed, a primary hydraulic calculation is needed to extract pump set combinations that do not work. The primary hydraulic calculation is based on actual information, mainly about physical characteristics of the piping system, physical properties of oil, characteristics of pump units, flow rate of the initial station, and some basic requirements for pipeline operations. An effective state set (Wu, 1992) can be obtained through an integrated method of state propagation, function propagation, and removing invalid state sets. Therefore, the optimal solution to the model can then be obtained.

6 Case study

The Southwestern Multi-product Pipeline transports $0^{\#}$ diesel, $90^{\#}$ gasoline, and $93^{\#}$ gasoline in batches, with a designed transportation capacity of $1{,}000\times10^4$ t/a. The pipeline has two off-take stations, two pump stations, ten off-take and pump stations, and one terminal station.

Table 1 lists the operation data of the Southwestern Pipeline in March, 2008. The optimal result for the pump set is obtained after optimization using the dynamic programming model mentioned above. Then, electricity costs of the pipeline operation with and without considering regional electricity price differences are calculated separately, as shown in Tables 2 and 3, respectively.

Table 1 Product demands at each off-take station

Station	Product demand, m^3				
	Batch 1	Batch 2	Batch 3	Batch 4	Batch 5
Yulin	0	0	1326.3	11834.3	1326.3
Guigang	0	0	2652.5	11834.3	1061.0
Nanning	0	0	5305.0	23668.6	1326.3
Litang	0	0	2652.5	9467.5	265.3
Liuzhouku	0	591.7	10610.1	21301.8	0
Hechi	0	1775.2	2652.5	11834.3	0
Duyun	0	5917.2	5305.0	11834.3	0
Guiyang	0	18934.9	7957.6	9467.5	0
Anshun	0	13017.8	3978.8	1183.4	0
Qinglong	0	11834.3	3978.8	5917.2	0
Panxian	0	11834.3	3978.8	9467.5	0
Qujing	0	30769.2	2652.5	18934.9	0
Yangtianchong	132.6	18934.9	1326.3	23668.6	0

Notes: Batch 1, Batch 3 and Batch 5 are 93# gasoline; Batch 2 and Batch 4 are 0# diesel.

Table 2 indicates that when considering regional differences in electricity prices, the total electricity cost is minimized by adjusting the electricity consumption of each station, namely by enabling the stations with high electricity price to use less electricity while the stations with low electricity price use more electricity.

In order to further analyze the impact of regional differences in electricity prices, the optimal electricity cost considering the impact of electricity price is compared with the electricity cost of the actual operation and results are shown in Table 3.

As shown in Table 3, both the electricity consumption and the operation cost of the optimal pump set considering regional differences of electricity prices are less than actual operation cost. It saves 54.51×10^4 CNY and the economic benefit is obvious. Therefore, the optimal result considering regional difference of electricity price can be regarded as a reference for practical pipeline operation.

7 Conclusions

1) In this paper, a mathematical model is established to optimize the operation of a multi-product pipeline system, which can provide a guide for pipeline operators.

2) Based on the actual operation data of the Southwestern Multi-Product Pipeline, a mathematical model is developed to calculate the operation cost. After analyzing and contrasting the optimized results with the actual operation cost, it is

Table 2 Electricity cost considering and without considering the regional differences in electricity prices

Station	Electricity consumption, kWh		Electricity price CNY/ kWh	Electricity cost, ten thousand CNY	
	Considering	Without considering		Considering	Without considering
Maoming	1474244.0	1513976.0	0.67	98.28	100.94
Yulin	1419399.0	1418691.0	0.47	66.68	66.65
Litang	723518.30	740710.40	0.59	42.49	43.50
Liuzhou	747250.30	767409.30	0.59	44.33	45.53
Hechi	539721.50	802225.90	0.59	32.02	47.60
Luqiao	850857.60	806564.10	0.44	37.17	35.23
Xiasi	639808.20	638591.10	0.38	24.40	24.36
Duyun	453503.30	526151.60	0.40	18.20	21.12
Guiyang	388963.50	388116.50	0.40	15.61	15.58
Anshun	404890.00	405617.10	0.40	16.25	16.28
Qinglong	535675.20	534036.40	0.39	21.06	21.00
Panxian	607271.10	576529.10	0.42	25.58	24.28
Yangtianchong	88506.34	97944.88	0.48	4.29	4.75
Total	–	–	–	446.38	466.81

Table 3 A comparison of electricity costs between using regional price differences and actual flat-price cost

Station	Actual data			Electricity cost considering price differences		
	Electricity consumption kWh	Electricity price CNY/ kWh	Electricity cost 10^4 CNY	Energy consumption kWh	Electricity price CNY/ kWh	Electricity cost 10^4 CNY
Maoming	1459496.00	0.67	97.30	1474244.00	0.67	98.28
Yulin	1524400.00	0.47	71.62	1419399.00	0.47	66.68
Litang	884000.00	0.59	51.92	723518.30	0.59	42.49
Liuzhou	972940.00	0.59	57.72	747250.30	0.59	44.33
Hechi	778740.00	0.59	46.20	539721.50	0.59	32.02
Luqiao	1051200.00	0.44	45.92	850857.60	0.44	37.17
Xiasi (Xinshi Line)	21000.00	0.38	0.80	639808.20	0.38	24.40
Xiasi (Xiashi Line)	456750.00	0.38	17.42			
Duyun	617940.00	0.40	24.80	453503.30	0.40	18.20
Guiyang	416139.00	0.40	16.70	388963.50	0.40	15.61
	1113.00	0.65	0.07			
Anshun (Huashi Line)	297800.00	0.40	11.95	404890.00	0.40	16.25
Anshun (Shuangshi Line)	156000.00	0.40	6.26			
Qinglong (Qingsha Station)	589400.00	0.39	23.18	535675.20	0.39	21.06
Qinglong (Qingda Line)	73780.00	0.39	2.90			
Panxian	567450.00	0.42	23.90	607271.10	0.42	25.58
	17550.00	0.68	1.19			
Yangtianchong	140120.00	0.48	6.79	88506.34	0.48	4.29
Total	9525818.00		506.65	8873608.00		446.38

concluded that the optimal operation cost considering regional differences in electricity prices is significantly better than that of the actual cost.

3) Considering regional difference of electricity price along the pipeline is the core of this paper and it is the important innovation. However, this paper does not cover sensitivity analysis or stability of the model solution. They will be discussed in detail in the future work.

Nomenclature

a_{iu} , b_{iu} , c_{iu}	Characteristic coefficients of the efficiency performance curve of the *u*th pump in the *i*th station, dimensionless
$A_{i,u}$, $B_{i,u}$	Constants determined by the characteristics of the *u*th pump in the *i*th station and pump unit combinations, dimensionless
F^j	The total friction loss of the pipeline at the *j*th time step, Pa
F_{h}^j	The total pressure loss due to elevation variation at the *j*th time step, Pa
F_{p+1}^j	Friction loss along the pipeline between the initial station and the (*p*+1)th station at the *j*th time step, Pa
$\overline{F_{p+1}^j}$	Friction loss along the pipeline between the initial station and the high- or low-elevation points before the (*p*+1)th station at the *j*th time step, Pa
$F_{\mathrm{h},p+1}^j$	Pressure loss due to elevation variation between the initial station and the (*p*+1)th station at the *j*th time step, Pa
$\overline{F_{\mathrm{h},p+1}^j}$	Pressure loss due to elevation variation between the initial station and the high- or low-elevation points before the (*p*+1)th station at the *j*th time step, Pa
g	Acceleration of gravity, m^3/s
$H_{i,u}^j$	Pressure head provided by the *u*th pump unit in the *i*th station at the *j*th time step, m
JN	The number of time steps in a transportation cycle
L_{l}	The total local pressure loss of all the stations within the piping system, Pa
$L_{\mathrm{l},p+1}$	The total friction loss within stations before the (*p*+1)th station, Pa
$n_{i,u}^{\mathrm{r}}$	Rated speed of the *u*th pump unit in the *i*th station, r/min;
$n_{i,u}^j$	Speed of the *u*th pump set in the *i*th station at the *j*th time step, r/min
P_{e}^j	Terminal pressure of pipeline at the *j*th time step, Pa
$P_{g,\mathrm{spe}}^j$	The pressure of special point *g* at the *j*th time step, Pa
$P_{i,\mathrm{d}}^j$	Discharge pressure of the *i*th station at the *j*th time step, Pa
$P_{i,\mathrm{s}}^j$	Suction pressure of the *i*th station at the *j*th time step, Pa
$P_{i,\mathrm{d\,max}}^j$	Preset discharge pressure of the *i*th pump station at the *j*th time step, Pa
$P_{i,\mathrm{s\,min}}^j$	Preset minimum suction pressure of the *i*th station at the *j*th time step, Pa
$P_{i,\mathrm{s\,max}}^j$	Preset maximum suction pressure of the *i*th station at the *j*th time step, Pa
$P_{p+1,\mathrm{s\,min}}^j$	Preset minimum suction pressure of the (*p*+1)th station at the *j*th time step, Pa
$P_{p+1,\mathrm{s\,max}}^j$	Preset maximum suction pressure of the (*p*+1)th station at the *j*th time step, Pa
$P_{p,\mathrm{d\,max}}^j$	Preset maximum discharge pressure of the *p*th station at the *j*th time step, Pa
P_{s}^j	Pressure after the feed pump in the initial station at the *j*th time step, Pa
$P_{\mathrm{spe\_min}}^g$	Preset minimum pressure of the *g*th special point, Pa
$P_{\mathrm{spe\_max}}^g$	Preset maximum pressure of the *g*th special point, Pa
$P_{\mathrm{spe\_min},p+1}$	Preset minimum pressure of the high-elevation points before the (*p*+1)th station, Pa
$P_{\mathrm{spe\_max},p+1}$	Preset maximum pressure of the low-elevation point before the (*p*+1)th station, Pa
Q_i^j	Flow rate of the *i*th station at the *j*th time step, m^3/s
$Q_{\max}^j$	Maximum transportation capacity at the *j*th time step, m^3/s
Q_1^j	Flow rate at the first station at the *j*th time step, m^3/s
S_i	Electricity price in the *i*th station, CNY/kWh
Δt_j	Step length of the *j*th time step, s
UN_i	The number of pump sets in the *i*th pump station
V	The total volume of fluids transporting in a pipeline in a transportation cycle, m^3
V_{cut}^j	The total throttle loss of the pipeline at the *j*th time step, Pa
$V_{\mathrm{cut},p+1}^j$	The total throttling loss within stations before the (*p*+1)th station, Pa
$W_{i,u}^j$	Operation state of the *u*th pump unit in the *i*th station at the *j*th time step
ρ_i^j	Product density at the *i*th station at the *j*th time step, kg/m^3

Superscripts and subscripts

d	Discharge pressure
dmax	Preset maximum discharge pressure
in	Suction pressure
smax	Preset maximum suction pressure
smin	Preset minimum suction pressure
g	Special point number
i, *p*	Station number, and for the initial station, *i*=1, *p*=1
j	Time step number
u	Pump sets number

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