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OPTIMIZATION OF PUMP ENERGY CONSUPTION IN OIL PIPELINES

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ABSTRACT

In the present work an optimization study was conducted with the objective of providing pipeline operators with a simple, spreadsheet-based computational tool to help decrease the electrical energy consumption associated with a particular transport operation. The methodology proposed encompasses the construction of a database of information on the pipeline regarding pumping power consumption, for all possible pumping arrangements and flow rate ranges considered viable for the pipeline. This database is fed to a spreadsheet programmed to calculate the minimum pumping cost for a particular operation. This calculation takes into account, the volume of product to be transported, start and finishing times, fluid properties, and the possibility of the existence of a low and a high electricity tariff based on geographical location and time of the day. The methodology was applied the ORBEL II pipeline in Brazil, and two case studies were conducted. Significant cost savings were obtained by the use of the methodology developed.

INTRODUCTION

The operation of a liquid hydrocarbon pipeline is normally conducted after a request is issued from the company's logistic department, through a daily operation program. This document contains the total volume to be transported of a specific product, a starting and a final time of operation, and a pump arrangement to be used with that particular operation. The pump arrangement indicated by the logistic department is chosen based on the ratio of total volume to be transported by the available time interval for the operation. The time interval is determined as a complex combination of logistic factors that include, among others, need for the product at a delivery point, availability of the product at a terminal base, dockage time of tankers at marine terminals, schedule of tankers arrival, etc. There is also the requirement that the pipeline be programmed in such a way that avoids flow shutdown and the associated re-starting problems.

For pipelines that have a number of pumping stations installed, each one equipped with several pumps, there are a variety of possible pump arrangements that will satisfy a certain programmed operation with respect to the volume transported and the total time of the operation. However, most of the time the arrangement proposed does not take into account the additional constrain of minimizing the cost of the transport operation. It is common nowadays to have pipeline's pumping stations submitted to different electricity tariffs that may depend on the hour of the day, season of the year or geographical location.

The objective of the present work is to develop a simple, spread-sheet-based computational tool to help pipeline operators choose pump arrangements that will minimize energy consumption, for a particular programmed transport operation, while taking into account the pipeline maximum pressure limits, fluid characteristics and energy cost variations.

The study conducted involved two phases. In the first phase a complete thermo-hydraulic simulation of the pipeline of interest was conducted. In our case, the commercial software Stoner Pipeline Simulator version 9.31 was used. The objective of the simulations was to generate data for the power consumption required for several transport operations, characterized by the complete flow rate range and all pumping arrangements considered viable for the pipeline under study. From the simulation results obtained, the flow rates that generated the minimum power consumptions for each pumping arrangement were identified and stored for later use.

In the second phase of the work all the power consumption data generated was exported to a spreadsheet that was programmed to calculate the minimum energy cost of a particular operation. Once the spreadsheet is fed with the data, there is no more need to run the thermo-hydraulic simulations. The input parameters needed for the spreadsheet calculations are the operation starting and finishing times, the total volume to be transported and the product characteristics. The algorithm created in the spreadsheet calculates the cost of all possible pumping arrangements that could meet the operation requirements, selecting the one with minimum cost. The possible electrical tariff variation during the interval imposed for the operation is taken into consideration in the cost calculations.

A review of the open literature has demonstrated that there is a lack of work devoted to develop a simple tool to help operators meet the programmed transport task and yet minimize energy consumption. During the design stages of a pipeline project it is common to direct a significant effort toward the specification and location of pumping and compression stations so that the different possible programs for which the line was designed are met with minimum cost of operation [1,2]. Also, for pipelines designed for flexible operation, monitoring of the power consumption of the pumping stations can help operators meet the electricity supply contracts that are based on variable tariffs [3]. Also, the literature mentions studies that aim at optimizing the pipeline operational variables by employing fuzzy logic and real-time monitoring of pump stations set points [4,5], and expert systems for analyzing and forecasting abnormal situations [6].

DESCRIPTION OF THE PIPELINED STUDIED

The case studied in the present paper is based on the data from the ORBEL II pipeline, operated by TRANSPETRO – Petrobras Transportes S.A.. The pipeline model was developed by TRANSPETRO [1] and tuned by the authors using operational data.

ORBEL II transports crude oil from the CEL marine terminal and the REGAP refinery. Besides the main pumping station at CEL, the pipeline has two intermediary pump stations called ESTAP e ESMAN. The cost of energy to run the pumps may change depending on the region where the station is located and also with the time of the day. In the present study two electricity tariffs are considered: a high tariff period between 6:00pm and 9:00pm, and a low tariff period for the rest of the day.

The ORBEL II pipeline has a total length of 358.4km (222 miles) with a nominal diameter of 609.6mm (24 in), what produces a total volume of 97,267m3. Figure 1 illustrates the pipeline divided into three sections using the main stations as limits.

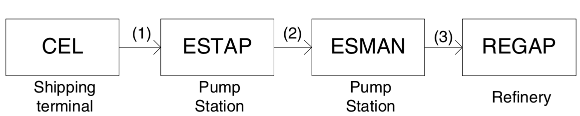

Figure1-Pipeline sections diagram

To facilitate the modeling, one supply tank at CEL and one delivery tank at REGAP are considered. There are no delivery points along the pipeline. The number of pumps installed at each station and the available maximum power are presented in the Table 1.

The model has been set to handle only a liquid phase, employing an isothermal calculation. The thermal variation effects are expected to be negligible since the oil flows at ambient temperature (68ºF) inside the pipeline, which is buried in all its extension.

Table1 – Maximum power and number of pumps at the stations

Station	No. of Pumps	Max. Power kW(hp)
CEL	03 (+1 spare)	2237 (3000)
ESTAP	03 (+1 spare)	1864 (2500)
ESMAN	04 (+1 spare)	746 (1000)

A typical crude oil used in the ORBEL II operations has a specific gravity (SG) of 0.891 and dynamic viscosity of 47.7cP. These values were used in the present analysis.

All the pump stations have P-I-D controlled valves that allow controlling the process automatically. In this situation the control valves are used to keep the power and pressure downstream of pumps below the operational limits. For instance, if the pump power surpasses the setpoint then a control valve partially closes to decrease the flow rate.

The pump arrangement indicates the number of pumps running at each station. For example, the arrangement 3+3+4 means that three pumps at CEL, three pumps at ESTAP and four pumps at ESMAN will be running. The other valid pump arrangements for the pipeline are: 2+2+3, 2+2+0, 1+1+0. Table 2 indicates the flow rate range for each pumping arrangement allowed in the pipeline operation. The minimum and maximum limits presented in the table are imposed by pressure limits in the pipeline. The pressure limits exist to prevent pump overheating (high flows), cavitation (low pressure) and to avoid column separation. The pressure limits are also set to maintain the pressure below the values of the hydrostatic pressure test for the line.

Table 2 – Flow rate range of the arrangements

Pump Arrangement	Minimum Flow (m^3/s)	Maximum Flow (m^3/s)
3+3+4	0.230	0.410
2+2+3	0.195	0.330
2+2+0	0.165	0.275
1+1+0	0.085	0.180

SIMULATION AND SOLUTION TECHNIQUE

In the simulation phase of the work the model for the pipeline was run with the objective of generating data for the total power consumption for each pumping arrangement, as a function of flow rate. The different flow rates were obtained by adjusting the control valve setpoints.

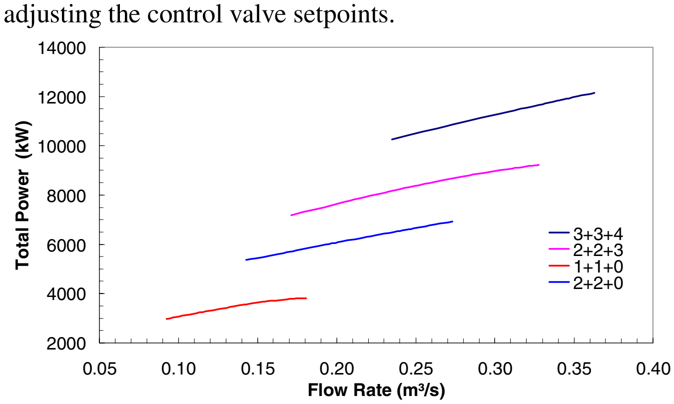

Figure 3 – Total pumping power required as a function of flow rate.

The results obtained for the total power consumption are presented in Fig. 3. As can be seen in the Fig. 3, the total power consumption increases with flow rate for each pump arrangement.

The specific power consumption however, decreases with flow rate, for the same pump arrangement. These results are presented in Fig. 4. The results of Fig.4 indicate that the minimum power consumption occurs at the maximum flow rate, for a particular arrangement. This way, the transport of a fixed volume of product will require less total energy if the maximum flow rate for the pump arrangement chosen is employed. The explanation for that behavior comes from the fact that at maximum flow rate the control valves are fully open, thereby imposing the minimum pressure drop to the flow. Figure 4 also shows that the different pump arrangements have many overlapping areas and that the arrangements employing fewer pumps will yield the smaller energy consumptions.

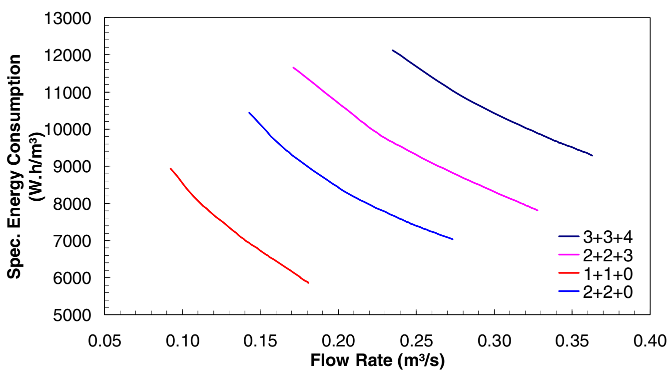

Figure 4 – Pump specific energy consumption as a function of flow rate.

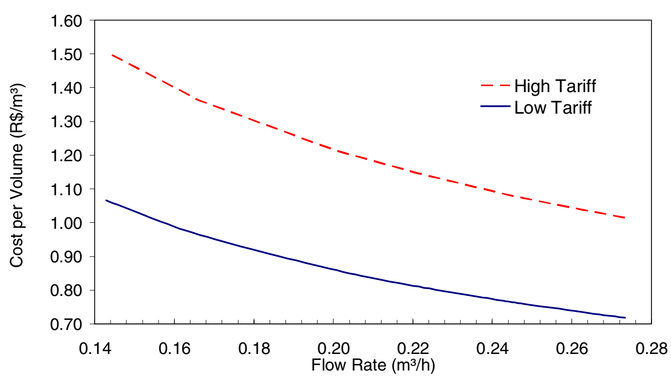

Figure 5 – Specific energy for high and low tariff period (arrangement 2+2+0)

As already mentioned, the electricity tariff to be applied is determined by the geographical location of the pump station and time of the day. In the present calculations a high tariff was used from 6:00 pm to 9:00 pm, while a low tariff was used for the rest of the day. In Fig. 5 the specific pumping cost for the 2+2+0 arrangement is presented as a function of the flow rate. The total pumping cost is given by Eq. (1):

$$COST_{TOTAL} = COST_{HIGH} + COST_{LOW} \qquad (1)$$

where,

$$COST_{HIGH} = V_{HIGH} \sum_{i=1}^{3} c_i \cdot kh_i \qquad (2)$$

and,

$$COST_{LOW} = V_{LOW} \sum_{i=1}^{3} c_i \cdot kl_i \qquad (3)$$

In the above equations, the index i represents the pump station (1, 2 and 3, respectively for the stations CEL, ESTAP and ESMAN), c_i is the station specific energy consumption, kh_i and kl_i are the high and low electricity tariffs applied to a station i, and V_{HIGH} and V_{LOW} are the total volumes to be moved during the high and low tariff periods, respectively.

The mean flow to accomplish the programmed schedule of product transport is calculated by:

$$Q_m = \frac{V_m}{t_m} \qquad (4)$$

where V_m is the total volume to be transported, starting at time t_s and finishing at time t_p. , so $t_m = t_p - t_s$. In case Q_m does not coincide with the highest flow rate for the pump arrangement, the minimum specific energy consumption will be obtained by a combination of two different arrangements, each one operating at its maximum flow rate. Equation (5) gives the total pumping period of arrangement *a,* in a situation where two arrangements *a* and *b*, are used:

$$t_a = \frac{V_m - Q_b \cdot t_m}{Q_a - Q_b} \qquad (5)$$

where Q_a and Q_b are the maximum flow rates of arrangements *a* and *b,* respectively, and $t_m = t_a + t_b$. The sumation of the electricity costs of arrangement *a* and *b* will give the total cost. In order to conclude the optimization procedure it is necessary to adjust the most economic pumping arrangement to operate during the high tariff period.

A Microsoft Excell worksheet was developed to select the most economical arrangement for a particular operation. Using the total volume to be transported, start and finishing times, specific energy consumption for each pumping arrangement and oil properties, the worksheet performs the following steps:

1. Calculate the mean flow, Eq. (4);
2. Calculate the period of operation with each arrangement, Eq. (5);
3. Identify the number of high tariff hours in the entire operation period;
4. Distribute the period of operation of the most economical arrangement calculated in item (2) among the high tariff periods identified in item (3). If necessary, complete the high tariff periods with the available period of operation of the other, higher cost, pumping arrangement;
5. Distribute the remaining time (if any) of operation of the most economical arrangement among the remaining low tariff periods. Complete the remaining low tariff

periods with the available operation period of the higher cost pumping arrangement;
6. Calculate the total cost of operation of each arrangement; Eq. (1);
7. Execute steps 2 to 6 for all possible combinations of arrangements;
8. Select the most economical arrangement.

The minimum specific energy consumption for other oils is obtained through correlations as shown in Fig. 6, so there is no need to conduct further calculations of the thermo-hydraulic pipeline model.

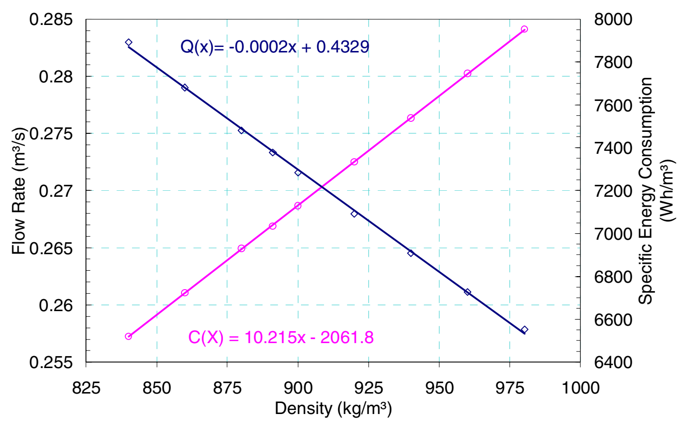

Figure 6 – Density influence on the maximum flow rate and minimum specific energy consumption. Pumping arrangement 2+2+0.

CASE STUDIES

Case Study 1 - The first case studied is originated by a document issued by the logistic department that calls for a transfer of 43,000m³ of crude oil, starting at 10:00am, and finishing two days later, at 12:00am. The document suggests a 2+2+0 arrangement.

For the given conditions, the operation period is 50.5 h and the mean flow is 851.5m³/h. For the 2+2+0 arrangement suggested by the logistic department, the pumps have to work at a flow rate below its maximum (and more economical) value of 984 m^3/h. This option will produce a high energy consumption and cost. This is illustrated in Table 3 as Option 1.

In case the pipeline is operated at the maximum flow rate for the suggested pumping arrangement, the total cost would be lowered, but the operation would finish before the specified time, leaving the line idle. This result is illustrated in the table as Option 2.

When the maximum flow rates of arrangements 2+2+0 and 1+1+0 are combined to produce the required mean flow rate, the program is obeyed and cost is reduced (Option 3). The optimal adjustment is obtained by distributing the period of utilization of pumping arrangement 1+1+0 between the high tariff periods. This is illustrated as Option 4. The savings obtained by the optimization are of the order of 13%.

Figure 7 indicates the optimal distribution of pumping arrangements. The yellow bar is the total operation time. The green bars indicate the high tariff periods. The red and blue bars represent, respectively, the calculated, optimum periods of operation of pumping arrangements 1+1+0, and 2+2+0.

Table 3 – Case Study 1: Pumping Cost Optimization

	Finish time	*Duration*	*Mean Flow m^3/h*	*Cost US$.*	*Saving %*
Option 1	12:30	50.5	851.5	11,682.15	
Option 2	5:42	43.7	984.0	10,875.23	6.9
Option 3	12:30	50.5	851.5	10,221.27	12.5
Option 4	12:30	50.5	851.5	10,100.77	13.5

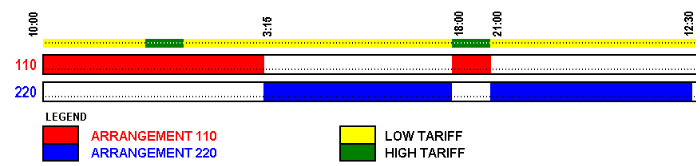

Figure 7: Optimal distribution of pumping arrangements – Case Study 1

Case Study 2 - A second operational document requires that a total volume of 63,000m³ of crude oil should be transported, starting at 12:30pm and finishing two days later at 16:30pm. The suggested arrangement is 3+3+4.

The mean flow calculated for the suggested arrangement (1211m³/h) is less than the maximum flow rate for that arrangement, what suggests that a combination of two pumping arrangements should yield a more economical operation.

Table 4 shows results generated by the spreadsheet developed. It can be seen that there are four options to carry out the required operation and that option 4 is the most economic one, representing savings of the order of 16%. Figure 8 shows the optimal distribution of pumping arrangements.

Table 4 – Case Study 2: Pumping Cost Optimization

Option		*LTP (h)*	*HTP (h)*	*Mean flow m^3/h*	*Partial Costs (US$)*	*Total Cost US$*
1	334	46	6	1211		***21,562.32***
2	220	12.29	3.00	98.00	3,893.47	***19,384.82***
	334	33.71	3.00	1306.34	15,491.34	
3	110	5.50	2.02	650.84	1,085.99	***19,916.43***
	334	40.50	3.98	1306.34	18,830.44	
4	**223**	**33.02**	**6.00**	**1180.00**	**12,874.90**	***18,172.39***
	334	**12.98**	**0.00**	**1306.34**	**5,297.49**	

LTP: low tariff period
HTP: high tariff period

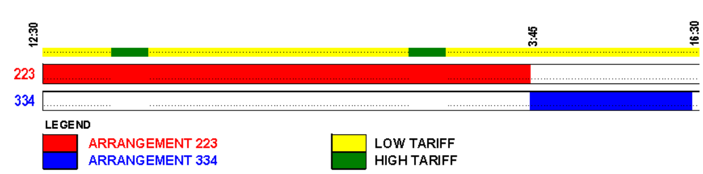

Figure 8: Optimal distribution of pumping arrangements – Case Study 2

CONCLUSIONS

The present paper presented a methodology for the optimization of pumping costs in pipeline operations. The proposed method is based on information generated via a detailed thermo-hydraulic simulation of the pipeline for all possible pumping arrangements and flow rate ranges considered viable for the operation of the particular line under study.

The information generated is fed to a spreadsheet programmed to calculate the costs associated with all viable pumping arrangement for a given operation. Among those, the program selects the one that is associated with the minimum pumping cost. Different electricity tariffs are considered depending on geographical region of the pumping station and time of the day.

The methodology was applied to an actual pipeline, the ORBEL II operated by TRANSPETRO/PETROBRAS, that transports crude oil from a marine terminal to a refinery. The pipeline is 358-km long and have three pumping station with a total of ten pumps installed.

Two case studies were presented of actual operational demands for the pipeline. The results obtained indicate that significant cost savings can be obtained by the proper distribution of pumping arrangements along the time interval set for the transport operation.

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