Monitoring of technological processes and assessment of technical condition of pumping units

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Abstract. Remote monitoring of pumping equipment operation in real mode is being widely introduced at oil and gas industry enterprises. The controllers applied in this process enable preventing progressive destruction of equipment and emergency failures and implementing automatic control of machines’ operation. The actual data collected by these controllers is transferred to the company's servers and makes it possible to effectively set and address various tasks on equipment maintenance. However, there is still insufficient number of applications to address the problems of pumping equipment operation. The presented paper is aimed at resource efficient operation of equipment by obtaining the information on both actual and predicted technical state of the equipment in real-time mode. The main performance characteristics of a pump deteriorate in the process of its operation, followed by an increase in specific power consumption for injection (with the reservoir properties unchanged). Economic losses due to pump's wear and tear are determined by the price of electricity and the cost of overhauling. Implementation of the designed monitoring system will make it possible to automatically decide whether further operation of the pump is unprofitable and if it needs to be overhauled. Based on the analysis of the trend of monthly unit costs, the pumping unit will be timely removed for major overhaul when the trend reaches its minimum, which shall provide an average annual economic benefit up to 4,000,000 rubles per pumping unit.

1. Introduction
In recent years, the problem of the efficient operation of equipment has been particularly challenging for the oil industry.

The technologies being introduced to optimise production processes can not be used without control and prediction systems requiring modern criteria for evaluation of the technical condition that can be easily adapted to automated monitoring systems [1,2].

2. Problem statement
It is common knowledge that the operating costs borne by the upstream companies to maintain their pump stock are quite high. The existing preventive maintenance (PM) system does not guarantee efficient operation of pumping units (PU), since its scope includes time- and volume-based maintenance and repair works, without consideration for the actual condition of equipment, real operating loads and specific process characteristics that affect the performance of pumps. The PM system has a preventive function and is aimed at preventing the failures. At the same time, the PM
design standards do not take into account the wear rates of the equipment’s operating components that depend on a variety of interdependent factors.

Pumping equipment monitoring is growing more relevant as the energy prices increase, so enterprises in the region turn towards servicing equipment based on its technical condition along with the application of predictive diagnostics. Objectives in this area become a priority for professionals seeking to reduce energy consumption and prevent downtime of the company's process-related assets resulting from equipment breakdowns. In this regard, systems designed for technical diagnostics of pumping equipment in real time, based on controlled parameters, are widely used in all areas of activity that involve the use of pumps. The main controlled parameters of pumping units are the following:

1. Pressure at the pump suction and discharge lines;
2. Flow rate of the pumped fluid;
3. Pump unit efficiency;
4. Per-unit energy consumption for pumping;
5. Vibration;
6. Temperature of bearings and electric motor winding;
7. Electric motor currents and voltages;
8. Pump and motor operating time.

Controllers installed on the units are designed to prevent "avalanche" (progressive) destruction of equipment and emergency failures, as well as perform automatic control of the units. The continuous data collected by the controllers is sent to the company's servers and may be used to set and address various tasks associated with equipment maintenance. However, the services addressing the problems of pumping equipment operations are quite limited at the moment; therefore, the development of services is of practical importance.

The most important task for mechanical engineering teams is the timely pump shutdown for overhaul.

3. Justification of the time for pump shutdown for overhaul
In the course of pump operation, the pump mechanical performance deteriorates, which is accompanied by an increase in the per-unit electricity consumption during injection (with the reservoir characteristics unchanged). Pumps are usually rejected based on such technical parameters as reduced flow, pressure, or efficiency, while the economic indicators are ignored. On the other hand, it is clear that given expensive overhaul and cheap electricity, it makes sense to operate pumps even with very significant wear, i.e. at low efficiency. In a reverse situation, when the electricity cost is high and the overhaul is cheap, a better option would be to conduct overhaul more often, avoiding significant wear of the pumps. Thus, the question of whether it is time to send a pump for overhaul should be addressed upon consideration of both technical and economic factors.

The mechanical characteristics of sectional centrifugal and screw pumps can only be restored during overhaul. The pump maintenance cycle (time between overhauls) may include many types of maintenance, but none of them affect the mechanical characteristics of the sectional pump, except for overhaul. During pump operation, the pump mechanical performance deteriorates and, consequently, the per-unit electricity consumption for fluid pumping increases. At a certain point, the steady increase in power costs lead to the situation when further operation of the pump unit is inefficient without restoring the operating parameters.

The works [3-5] discuss the efficient operation of high-pressure pumping units, and in particular, propose and justify the choice of the optimal time between overhauls. The overhaul duration should be planned the way which would minimise the average total cost of excessive electric power consumption caused by the wear of the pump's fluid end (diffusers, impellers, seals), as well as the cost of the works related to overhaul (dismantling, installation, transportation, overhaul) for the planned period. Wear costs (costs associated with the wear of the fluid end of the pump) are determined by the price of
electricity, pump delta pressure, the efficiency, the volume of fluid pumped and, if calculated per one hour of operating time, are calculated as follows:

\[
\frac{CT_{overhaul} + \sum_{i=1}^{II} H_{ep} \left( \frac{\Delta P_i}{H_{agr}} - \frac{\Delta P_i}{H_{agr}} \right) dW_t}{W_{\text{cvs}}, \text{wear}(t)}
\]

Assuming that the pump is a perfect match for the reservoir and the reservoir head remains unchanged in the course of operation. The per-hour costs caused by pump wear depend on the duration of the time between overhauls (TBO) and have a minimum value. By building this dependence, we can obtain both the optimal pump overhaul period and the minimum possible costs associated with pump wear.

The proposed method can be still applied; however, since each pump has its own wear rate, it gives only an average TBO. In addition, at the time of planning, there is no data on the overhaul and electric power prices at the time of pump shutdown for overhaul. In the current situation, on the back of the introduction of pumping equipment monitoring systems, it becomes possible to automatically track the operation of each pump unit and automatically detect the inefficiency of further pump operation, i.e., the need for overhaul.

To make the ultimate decision, the controlled parameters must include the following:
1. pump operating time;
2. active power consumption;
3. fluid flow and head.

Considering that the unit efficiency is determined by the pump hydraulic horsepower and the electric power consumption:

\[
\eta_t = \left( \frac{P_{\text{flow},\text{intake}}}{W_t} \right) Q_t
\]

where \( P_{\text{flow}} \) is the pressure in the discharge line;
\( P_{\text{intake}} \) - pressure in the suction line;
\( Q_t \) - fluid flow rate;
\( W_t \) - active power consumption.

and per-hour consumption, where is 1 hour, we obtain:

\[
\frac{CT_{overhaul} + \sum_{i=1}^{II} H_{ep} \left( \frac{W_i - W_1}{Q_t - Q_1} \right) Q_t dW_t}{W_{\text{wear}}, \text{hour}(t)}
\]

Setting a certain time step \( T \) (day, week, decade, month), at the end of each step, we calculate the wear costs, taking the current pump operating time as TBO. Then we track the parameter trend, and as it starts showing a steady growth (several steps in a row), we issue a recommendation to shut down the pump for overhaul. Prices for overhaul and electricity are taken as current prices at the time of calculation.

Thus, regular automated monitoring of the pump unit operating parameters enables us to automatically detect the inefficiency of further pump operation and the need for overhaul.

The developed algorithm for the pumping equipment shutdown for overhaul assumes the following possible optimum criteria:
1. Minimum costs associated with the wear of the pump's fluid end per 1 hour of operation:
2. Minimum costs associated with the wear of the pump's fluid end per 1 cubic meter of pumped fluid.
The time of the unit shutdown for overhaul is identified as follows:

1. The costs of excessive power consumption associated with pump wear are calculated for each month. To do this, the difference between the electricity actually consumed and the electricity that a new pump would have consumed for the same work is calculated based on the monthly summary of electricity costs, flow rate, and pump head data. These overruns are added up from the start of the pump operation.

1. For each month, the financial losses associated with pump wear and tear (excessive electricity consumption and the costs of overhaul) are calculated as the total of the pump overhaul cost and the cost of excessive electricity consumption. The prices of overhaul and electricity valid at the time of decision-making are taken for calculation.

Depending on the selected criterion, the resulting losses are divided by the total pumping volume or operating time

\[
C_{\text{wear}}^{\text{volume}} = \frac{C_{\text{overhaul}} + H_e \sum_{n=1}^{N} (A \eta_n (P_{\text{flow}} - P_{\text{intake}}) \cdot A V_n)}{\sum_{n=1}^{N} A V_n}
\]

\[
C_{\text{wear}}^{\text{hour}} = \frac{C_{\text{overhaul}} + H_e \sum_{n=1}^{N} (A \eta_n (P_{\text{flow}} - P_{\text{intake}}) \cdot A V_n)}{\sum_{n=1}^{N} A V_n}
\]

where \(C_{\text{wear}}\) is the cost per unit of time determined by the wear of the pump's working parts;

\(C_{\text{overhaul}}\) – the cost of overhaul (including the costs of pump transportation, installation and dismantling);

\(A_n\) - electricity consumption within the step;

\(V_n\) - volume of fluid pumped within the step;

\(H_e\) - price of electricity;

\(t_n\) - pump operating time within the step;

and per-unit operating costs associated with the pump wear are obtained.

The monthly trend of per-unit costs is built, and once the trend attains its minimum, a decision is made to shut down the unit for overhaul.

4. Algorithm implementation

The developed algorithm has been implemented in the pump unit automated monitoring system. Its main features:

1. Visualisation of the current state of pumping units
2. Monitoring of the pumping unit technical condition
3. Evaluation of compliance of the pumping equipment installed with operating conditions at the sites;
4. Selection of pumping equipment matching the site parameters;
5. Predicting the needs for maintenance and repair;
6. Predicting the need for diagnostics;
7. Justification of the need to shut down pumping equipment for overhaul;
8. Analysis of energy consumption by pumping units.

Figure 1 shows a photo of the automated monitoring system implementation.
Figure 1. Flow diagram of the downhole pumping equipment configuration. 
1 - SCP unit 180x1422, 2 - vibration sensor, 3 - monitoring station, 4 - display of the main unit operation parameters in the pump box, 5 - computer in the control room (corporate network).

5. Discussion
The implementation of system will offer a new way to develop a preventive pump unit maintenance schedule using the method of determining the optimal pump unit overhaul period [6,7], assuming that the pump efficiency will be restored after attaining a certain critical value. Table I provides the calculation of the yearly cost advantage due to the implementation of this method on a single SCP 180x1422 pump unit for different efficiency loss intervals.

Table 1. Calculation of the yearly cost advantage due to the implementation of the method per pump unit

| No. | Initial efficiency, % | Final efficiency, % without implementation | Final efficiency, % after implementation | Time between overhauls, days without implementation | Time between overhauls, days after implementation | Yearly cost advantage, thousand rubles |
|-----|-----------------------|---------------------------------------------|------------------------------------------|-----------------------------------------------|-----------------------------------------------|-------------------------------------|
| 1   | 69                    | 60                                          | 65.4                                     | 365                                           | 167                                           | 1,680                               |
| 2   | 60                    | 50                                          | 56.1                                     | 365                                           | 143                                           | 2,900                               |
| 3   | 50                    | 40                                          | 46.7                                     | 365                                           | 119                                           | 4,910                               |
| 4   | 44                    | 35                                          | 42.1                                     | 365                                           | 107                                           | 6,930                               |

6. Summary and conclusions
Modern level of diagnostic tools development allows continuous monitoring of pump unit parameters in order to control their technical condition. At the same time, regulation is required in respect of the monitoring and analysis of the vibration level, temperature, leaks, pressure parameters, efficiency, and power consumption. According to the pre-calculated feasibility study (Table I), the implementation of monitoring system based on the method for determining the optimal pump unit overhaul period will produce an average yearly cost advantage to the amount of 4,000,000 rubles per pump unit.

The pump unit automated monitoring system is designed to ensure continuous monitoring, collection, storage and visualisation of process and technical data of operating units with the possibility to display current operational parameters and prevent deviations from the parameters set.
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