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ARTICLE

IMPACT OF THE GEOMETRICAL CONFIGURATION OF ELECTRICAL SUBMERSIBLE PUMP IMPELLERS ON RUN LIFE AND SAND STUFFING: A CASE STUDY AND RECOMMENDED PRACTICE

Masaad Eltigani

University of Khartoum, Faculty of Engineering, Department of Petroleum Engineering,
45 Al-Nil Avenue, P.O Box 321 Khartoum, Sudan
e-mail: masaadeltigani21@gmail.com
ORCID: 0009-0006-0258-4814

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Abstract: The objective of this study was to identify the root cause of the premature failures of electrical submersible pumps installed in an artificially lifted brown oil field located in southeastern part of Sudan, and to mitigate the causes in order to extend the pumps run life so oil production is increased and lifting costs are reduced. One of the standard failure finding procedures, known as Dismantle, Inspection, and Failure Analysis (DIFA) was used in this study to systematically tear down and inspect the failed pumps to find out the root cause of the failures. It was found that sand accumulation (stuffing) in the radial flow impellers was the cause of premature pump failures. The study has further elaborated on the technical reasons and justification as to why radial flow impeller pumps, despite their seemingly perfect design, were unable to produce sand while the mixed flow, under designed for the same well conditions, did. This finding was then experimented on many wells and proved to be correct as demonstrated in this paper. Eventually, the result was technically proved as being attributed to the geometrical shape of the impeller flow path. The study has then correlated sand stuffing failure with the flow path geometry of the impellers and eventually projected these results to an established specific speed model (N_s) with the recommendation of adopting a pump sizing approach in mild sand-producing oil wells to cater for the geometrical flow configuration of the pump impellers.

Keywords: lifting cost, run life, sand stuffing, electrical submersible pump, radial flow impeller, mixed flow impeller, geometrical configuration

1. Introduction

This study was motivated by frequent electrical submersible pump (ESP) failures that result in increased lifting costs and consequently higher unit production costs. ESPs are used extensively in the oil and gas industry as effective and economical modes of artificial lift for producing oil and water wells. Ideally, ESPs are designed to operate within an optimum operating range at the best efficiency point to attain the best performance and longest run life, which eventually results in the least lifting cost and the maximum company profit (Fig. 1).

However, due to adverse well and fluid conditions, properly designed ESPs may not be able to realize expected good performance and economics. The most frequently articulated concerns of ESP operators are that ESP workover costs are high and the perceived run life of ESP systems are too low. ESP suppliers work to ensure the proper sizing and application of ESPs while introducing new technologies and materials to improve system robustness.

A few factors have been shown to affect the run life of ESPs: equipment sizing, selection, operation, power quality, well deliverability and inflow performance, ESP operating temperature, solids production, free gas in pump, deposition, and corrosion [1–3]. Solids production, particularly sand production, which frequently occurs in centrifugal pumps, considerably shortens the run life of ESPs [1]. Sand production is known to damage ESPs through the actions of erosion and abrasion [4], which have already been identified and mitigated.

International professional associations, such as API (American Petroleum Institute), ANSI (American National Standards Institute), ASTM (American Society for Testing and Material) etc., have set many test standards and procedures for a wide range of industries including: oil and gas, power and energy, biomedical and healthcare, information technology (IT), telecommunications, transportation, nanotechnology, information assurance, and many more. These standards are designed to provide reasonable assurance that business objectives will be achieved and undesired events will be prevented, detected, and corrected. Pump users have intensively used them throughout the life cycle of the products from manufacturing till utilization and finally abandonment. DIFA as a standard procedure for root cause failure analysis is a good example.

The current experimental study on the premature failure of ESPs revealed that the frequent failure of pumps was mainly due to sand accumulation (stuffing) in the stages of radial flow pumps, rather than mixed flow pumps, and this was mainly due to the geometrical shape of the stage flow path. These findings indicate the existence of a relationship between sand stuffing; the geometry of the pump flow path, being either radial or mixed; and the run life of the pump. These conclusions are validated by existing technical material on the impact of the geometrical distribution of the components within the flow path, the mass, momentum, and energy transfer rates [5], and the specific speeds for different types of impellers [6].

In conclusion, based on this study's findings and supporting technical material on multiphase flow and specific speeds of fluid flow through impellers [5, 6] to achieve a longer pump run life and the least oil lifting cost, once sand production is confirmed by any mechanism, or if a sand production tendency is proved, the use of a mixed flow pump instead of a radial pump is recommended if the standard pump design program recommends a radial pump.

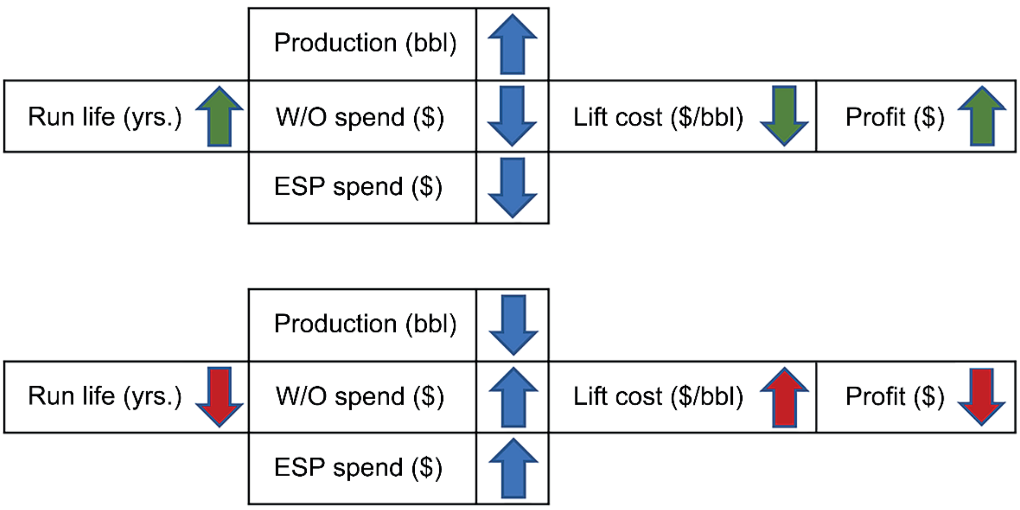

Fig. 1. Effect of ESP run life on oil lifting cost ($/bbl) and the related cost element

2. Material and Methods

This was intended to investigate and improve the performance (run life) of a population of over 200 ESPs. The Dismantle Inspection and Fault Analysis method, DIFA, a widely used standard procedure in the oil and gas industry, was employed in this study to identify the root cause of the frequent pump failures. It requires the involvement of high skilled professionals to work it out, from the data gathering stage, through equipment tear down and until the writing of the final DIFA report. Equipment tear down should be done very carefully by a skilled professional to ensure that evidence and clues as to the cause of the failure are not destroyed. The final DIFA report is used by both the operating company and the supplier for the development of new products and the improvement of existing ones so product performance will be improved in the next installation. The report is also used to settle contractual liabilities in the case of leased contracts and services when the cause of failure is confirmed and agreed to be either due to well conditions or a material issue.

3. Case Study

The data in Table 1 was extracted from a comprehensive pump performance database of pumps operated in a brown oil field located in the southeastern part of Sudan. The data presents the relevant well names, reservoirs, pump types, production data, fluid levels, sand accumulation, the number of pump failures, and the calculated failure indices that were used for performance monitoring and wells prioritization for root cause failure analysis task. Additionally, data from pumps pulled out of their holes and run in hole reports were reviewed and evaluated for any critical observations such as the presence of sand or foreign materials in the tubing or pump intake, scratches on the pump and motor housing, missing cable clamps, in addition to some other important observation during tear down such as the coloration of motor housing which may indicate overheating as a result of insufficient cooling fluid reaching the motor, or motor seal bursts which will burn the motor as the dielectric oil will be contaminated. All of these observations help the DIFA team to identify the cause of a fault with a very high degree of precision and implement mitigation actions.

Table 1. Samples from the electrical submersible pumps performance database*

No.	Well name	Reservoir	Pump type	Well test data				Failure index		
		Producing zone		Gross liquid rate [m^3pd]	Oil rate [m^3pd]	Water Cut [%]	Fluid level [m]	Sand fill rate [m/year]	Number of failures	Failure index [failure/year]
1	Wel-01	Reservoir E, F, 1A, and 1B	Mix 2000	760	615	19	160	**5.72**	**4.00**	**1.00**
2	Wel-02	Reservoir 1A and 1B	Mix 3000	1,477	266	82	539	**2.79**	**4.00**	**2.00**
3	Wel-03	Reservoir E, F, 1A, and 1B	Rad-10	505	220	56	1,257	**12.58**	**5.00**	**1.25**
4	Wel-04	Reservoir E and 1B	Rad-10	1,030	207	80	1,414	**5.84**	**7.00**	**1.40**
5	Wel-05	Reservoir E, F, 1A, and 1B	Rad-15	480	168	65	1,682	**12.67**	**9.00**	**2.25**
6	Wel-06	Reservoir 1B	Rad-15	217	139	36	1,134	**12.11**	**2.00**	**1.00**

* Calculated failure index numbers (last column) were used to indicate the failure frequencies per year and the need to revise the pump selection methods to reduce the failure index.

4. Observations, Findings, and Discussion

For the purpose of this study, a set of basic production, reservoir, well, pump, and workover data was collected for each well (Tab. 1). A failure index was then calculated to determine the failure frequency for each pump and to prioritize the wells for in-depth DIFA (Fig. 2).

The main observations were as follows:

1. Many ESPs have repeatedly failed prematurely (e.g., Wel-05, 2.25 failure/year).
2. All these premature failures were associated with sand-producing reservoirs (Reservoir E, F, 1A, and 1B), as confirmed by the pull reports such as the well (Wel-05) which experienced a sand accumulation rate of 12.67 m/year.
3. The DIFA found that the pump impellers were fully stuffed with sand.
4. The pump design, installation, and pulling reports indicated that the failed pumps were radial flow type pumps designed as per standard procedures to operate within optimum operating range at the best efficiency point (BEP).
5. The DIFA analysis showed that most of the premature failures occurred in the radial flow type pumps due to sand accumulation. As, a result, when the failed radial flow pump was replaced by a mixed flow compression to make up for the low rate, the run life increased remarkably in the same well and under the same conditions (Tab. 1, Fig. 2).
6. It was concluded that the under performance of the radial flow pumps in mild sand producing reservoirs is because of the geometrical configuration of the impeller flow path (Fig. 3).

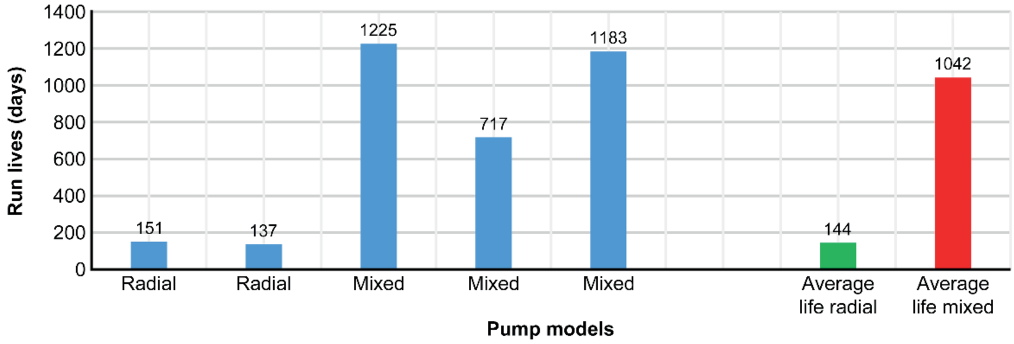

Fig. 2. Average run life for radial and mixed flow impellers modes operated at the same well and reservoir conditions

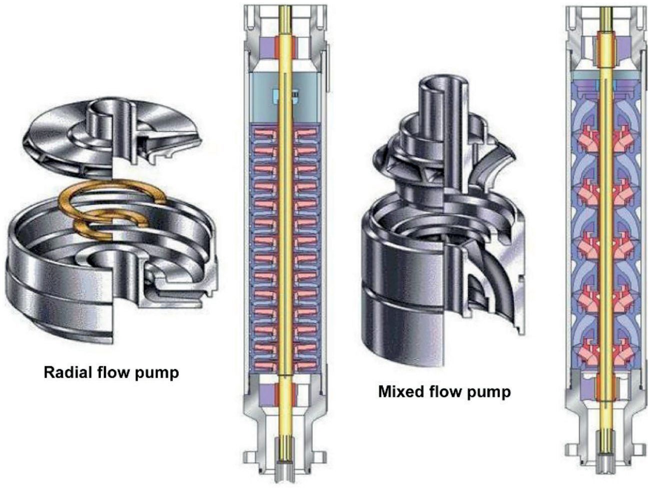

Fig. 3. Geometrical configuration (fluid flow path) of ESP radial and mixed flow pump types to illustrate right and forty-five degree angle that impact the sand settling inside the pump stage [9 , p. 46]

5. Theoretical Background

From a practical engineering point of view, a major design difficulty when dealing with multiphase flow is that the mass, momentum, and energy transfer rates and processes can be quite sensitive to the geometric distribution or topology of the components within the flow path. For example, geometry may strongly affect the interfacial area available for mass, momentum, or energy exchange between phases. Moreover, the flow within each phase or component will depend on that geometric distribution. Thus, we recognized a complicated two-way coupling between the flow in each of the phases or components and the geometry of the flow (as well as the rates of change in that geometry). The complexity of this two-way coupling presents a major challenge in the study of multiphase flows, and much remains to be done before even a superficial understanding is achieved.

The basic principle of a submersible pump is that the surrounding liquid (water or oil) after being subjected to great centrifugal forces caused by the high rotational speed of the impeller, lose their kinetic energy in the diffuser where a conversion of kinetic energy to pressure energy takes place. This is the main operational mechanism of radial and mixed flow pumps [5, 7].

The degree of kinetic energy loss and conversion to pressure is a function of the flow path or topology of the pump type. The flow path of a radial pump is assumed to be zigzag-shaped with right angle turns, while the flow path of a mixed flow pump is assumed to be zigzag-shaped with smooth, approximately 45° turns (Fig. 3). The configuration of the radial pump has great advantages in ideal conditions where no sand production is present, as the energy conversion results in high discharge pressure and low flow velocity. However, in a mixed flow pump, the configuration results in low discharge pressure but high flow velocity. Flow velocity is an important factor that governs sand precipitation in ESP stages. The effect of flow speed is best explained by the concept of specific speed, as derived in the following equations and Figure 4.

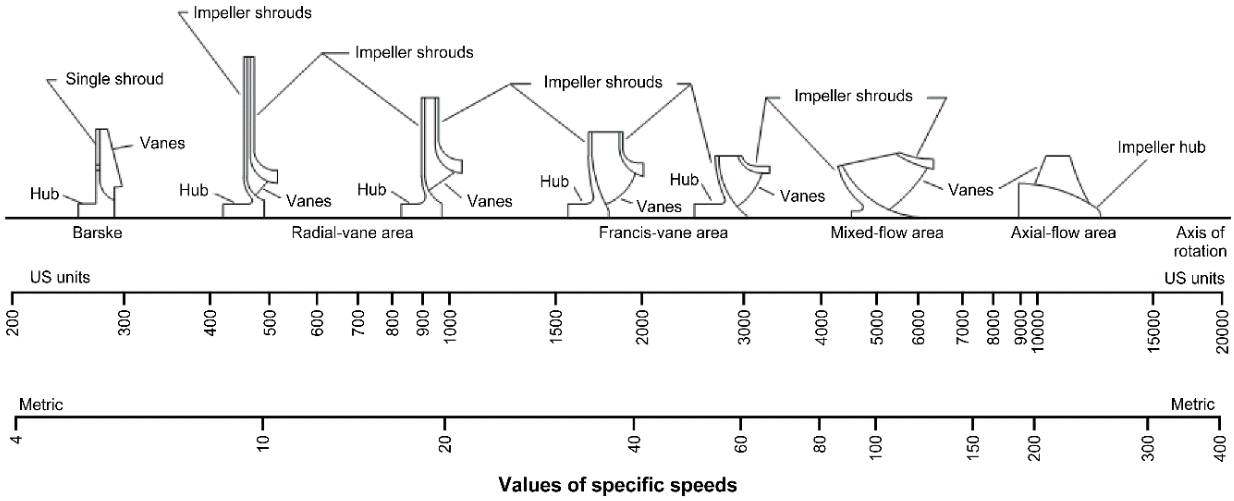

Fig. 4. Range of specific speed values for different pump types: radial, mixed, and axial flow (Courtesy of Hydraulic Institute Engineering data library, updated on May 26, 2020) [10]

5.1. Forces Acting at the Pump Stage

Two forces act on the fluid slurry at the pump stage: centrifugal force and gravitational force. The ratio between these forces is explained by the following equation:

$$\frac{Fc}{Fg} = \frac{mu\frac{2}{r}}{mg} = \frac{u2}{rg} = \frac{\omega 2r}{g} \tag{1}$$

where Fc is the centrifugal force and Fg is the gravitational force. For example, if $\omega = 3{,}600$ rpm and $r = 40''$, then this ratio is 131,673, which indicates that centrifugal force is dominant over gravitational force.

5.2. Specific Speed

This number characterizes the type of pump impeller in a unique and coherent way [6]. It is a dimensionless number derived from the following equation [8]:

$$N_s = \frac{N\sqrt{Q}}{H^{0.75}} \tag{2}$$

The same equation can be rewritten in terms of ω as follows:

$$N_s = \omega\frac{q^{0.5}}{H^{0.75}} \tag{3}$$

where:
N_s – specific speed, dimensionless number,
n – rotational speed, in revolutions per minute,
Q – total pump flow rate at best efficiency point in gallons per minute,
H – head per stage, in feet,
ω – pump shaft rotational speed [rpm].

6. Conclusions and Recommended Practice

This study examined the frequent premature failure of ESPs in oil fields in Sudan because this affects lifting costs and, therefore, overall production costs. The study concluded that frequent failures and short run life mostly occurred in radial flow pumps, while when replaced by mixed flow pumps operating under the same conditions, run life was remarkably improved. The DIFA of prematurely failed pumps showed that sand accumulation (stuffing) in the impellers was the cause of the failures. The study concluded that sand stuffing is a sand production issue, as it causes premature pump failures in addition to the already identified sand abrasion and erosion production issues.

Technical papers on the topology of multiphase flow patterns indicate that the main operational mechanism of radial and mixed flow pumps is that produced liquids, after being subjected to great centrifugal forces caused by the high rotational speed of the impeller, lose their kinetic energy in the diffuser where a conversion of kinetic to pressure energy takes place [5, 7]. The degree of kinetic energy loss and conversion to pressure is a function of the flow path or topology of the pump.

The study recommends obtaining a prior understanding of the sand-producing tendency of a producing zone prior to pump selection. In the event of premature pump failure, it is recommended that a DIFA, workover installation, and a pull report be undertaken to determine if an ESP must be used. It is then recommended to use mixed flow pumps to improve the run life and reduce operating costs.

Author contributions: The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

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