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A Review of the Electrical Submersible Pump Development Chronology

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Abstract

The electric submersible pump, also known as ESP, is a highly effective artificial lift method widely used in the oil industry due to its ability to deliver higher production rates compared to other artificial lift methods. In principle, ESP is a multistage centrifugal pump that converts kinetic energy into dynamic hydraulic pressure necessary to lift fluids at a higher rate with lower bottomhole pressure, especially in oil wells under certain bottomhole condition fluid, and reservoir characteristics. However, several factors and challenges can complicate the completion and optimum development of ESP deployed wells, which need to be addressed to optimize its performance by maximizing efficiency and minimizing costs and uncertainties. To analyze the performance of ESP deployed wells, the objective function must include various factors associated with fluids, reservoir inflow and outflow characteristics, and pump parameters. In particular, the inflow and outflow parameters include well configuration, and types of completion string (e.g. tubing sizes, and download completion hardware) while reservoir and fluid parameters include pressure, temperature, and PVT properties. Pump parameters include gas vacuum fraction, electrical and mechanical constraints, power requirements, cable requirements, downhole conditions, etc. Despite these challenges, ESPs' importance and efficiency necessitate an in-depth understanding of its origins and evolution over time, as well as the difficulties encountered in the oil industry. This paper aims to provide a comprehensive review of ESP's origin and development, including all prior studies that have influenced optimum development. The literature review is divided into four main sections: experimental investigations, numerical simulation studies, mechanical modeling, and in-depth studies on production optimization. By providing an in-depth analysis of previous work in each area, this paper aims to contribute to ongoing efforts to enhance ESPs' performance and efficiency in the oil industry.

Keywords: *electrical submersible pump; artificial lift; production optimization.*

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1- Introduction

In the oil production industry, initial production from a well often occurs naturally, with the bottom hole pressure being sufficient to overcome pressure losses along the flow path to the separator [1, 2].

However, as the reservoir's energy is depleted, the well's productivity may decline to the point where it is no longer profitable or even becomes non-productive. This situation arises when there is insufficient energy to lift the oil to the surface or when the surface pressure exceeds the bottom hole pressure due to various factors. In such cases, artificial lift methods are employed to restore or optimize productivity [3].

Among the different types of artificial lift systems used in the oil well industry, such as gas lift (GL), sucker rod pump (SRP), progressive cavity pump (PCP), and hydraulic jet type pump, the electric submersible pump (ESP) stands out due to its numerous advantages [4]. ESPs offer a high working rate ranging from 200 to 60,000 barrels per day (BPD) and can operate at depths of up to 15,000 feet (4,570 meters) [5]. Furthermore, ESP equipment is relatively cost-effective and can be easily operated both onshore and offshore. As a result, ESPs have gained significant attention and have been widely adopted in the oil industry. Throughout the history of artificial lift, there have been continuous efforts to develop and enhance ESP equipment and operational systems. Numerous researchers have conducted investigations to address challenges and improve the performance of ESPs over time [6, 7]. These investigations have focused on advancing the technology, mitigating operational issues, and optimizing the design and efficiency of ESP systems.

In this paper, we aim to provide a comprehensive review of the development chronology of electrical submersible pumps. By examining the key milestones, technological advancements, and research findings in the field, we seek to contribute to the understanding of ESPs and their evolution. A better understanding of the historical context and improvements made in ESP technology can inform future advancements and aid in optimizing the selection, installation, and operation of ESP systems for efficient oil production.

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2- Historical Overview

A key milestone in the oil industry was the development of electrical submersible pumps (ESPs), which revolutionized artificial lift techniques. Unlike other artificial lift methods like gas-lift or rod pumping, the creation of ESP cannot be attributed to a single person or time period.

In the late 1910s, a Russian engineer named Armais Arutunoff played a significant role in the development of ESP technology. In 1911, he established the Russian Electrical Dynamo of Arutunoff Company (REDA) and invented the submersible electric motor. Recognizing the potential of his ideas, Arutunoff embarked on a journey to Germany in 1919 and subsequently moved to the United States in 1923 to seek support for further development [6].

In 1926, Arutunoff was granted a US patent for the electrical submersible pump, covering the fundamental aspects of this innovative artificial lift method. The first successful ESP installation took place in the El Dorado field in Kansas during the same year [8]. The complete ESP unit comprises a motor, seal, and pump, which are run into the well at the bottom of the tubing string. A specialized three-conductor cable connects the motor to the surface, supplying power to the system. These components remain critical in modern ESP systems [9]. REDA, with over 90 years of experience, continues to be one of the world's leading producers of ESP equipment for the oil industry. The company has obtained more than 90 patents related to submersible equipment. Numerous other manufacturing firms in the US have connections to the initial REDA company.

ESPs have proven to be highly efficient in lifting large quantities of liquid, particularly in high-rate onshore and offshore applications. It is estimated that submersible pumping facilities now contribute to more than 10% of global oil production. Over the course of its history, ESP technology has undergone continuous improvement and innovation [10].

Significant advancements occurred in the 1950s with the introduction of "seal units" or protectors featuring mechanical seals. These improved ESP run times by providing better protection against well fluid leaking into the motor. Addressing the challenge of gassy wells, the industry saw further progress in the early 1970s with the introduction of the first rotary gas separator, which enhanced gas separation capabilities [11]. Another pivotal moment came in August 1977 when the initial variable speed ESP device was installed. The variable speed drive (VSD) allowed for the adjustment of the electric current frequency driving the ESP motor, enabling significant changes in the submersible pump's head performance [12].

By understanding the historical development of ESPs, researchers can appreciate the advancements made in the field and gain insights into the challenges that have been overcome. This knowledge serves as a foundation for ongoing research, development, and optimization of ESP systems to ensure efficient and reliable oil production (Fig. 1).

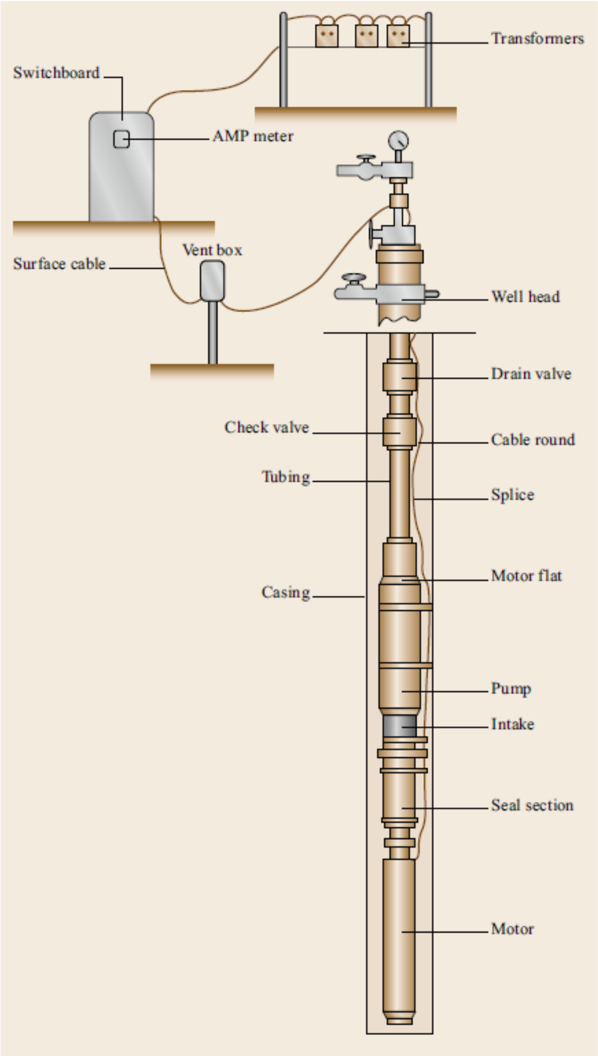

Fig. 1. ESP Components

3- Evolution of Electric Submersible Pump Studies

Over the past few years, the ESP technique has gained significant attention from researchers worldwide [13]. This can be attributed to the availability of data and advancements in computer capabilities, which allow for efficient handling of multi-constraint tasks. As seen in Fig. 2, the number of published papers on ESP has steadily increased over the past two decades. This growth in research is due to the continued development of ESP pumps and new technologies applied to different parts of ESP equipment. These advancements have increased the lifespan and overall benefit of ESP, making it a more attractive topic for researchers to explore.

4- Review of ESP Studies

The optimization of electric submersible pumps (ESPs) is a complex process with many variables, and each piece of equipment requires optimization to achieve the best possible results and reach the optimal production level [6, 14]. This section highlights some notable researchers who have focused their research on various areas of ESP operations and optimization tasks. Previous research has shown that gas accumulation can cause the hydraulic head of the ESP to deteriorate, and handling gas-liquid mixtures has become increasingly common over time. However, the actual mechanism of two-phase flow that affects ESP performance remains unclear due to the complex geometry of multistage ESPs and the unknown gas bubble breakup mechanism and coalescence that create two-phase flow [15].

This literature review focuses on studies related to the optimization of electric submersible pumps (ESPs). It is divided into four sections: Experimental Studies, Computational Fluid Dynamics (CFD) Simulations, Mechanistic Modeling, and Optimization Studies.

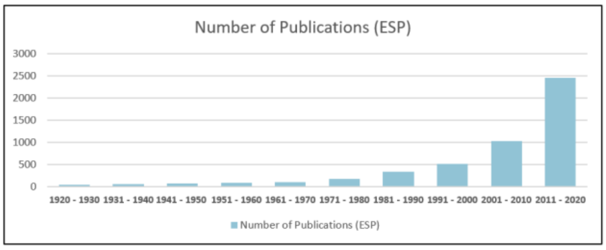

Fig. 2. The Number of ESP Publications Against Time (Curtin University – Library Database)

The Experimental Studies section discusses research that investigates various hydraulic elements affecting the boost pressure of ESPs. It covers topics such as the impacts of gas entrainment, fluid viscosity, and multiphase flow. The studies involve performance tests, correlation factors, adjustment factors, and empirical correlations to understand the behavior and performance of ESPs under different conditions. Some of the challenges identified include the unknown gas bubble breakup mechanism, gas-liquid flow behavior, and the effect of fluid properties on friction losses.

The Numerical Simulations Studies section highlights the use of CFD techniques to study ESP performance in single-phase and multiphase flow conditions. CFD provides a way to simulate the complex internal flow configurations of ESPs, which are challenging to explore through experiments. The studies discuss different modeling approaches, including the frozen-rotor interface model, transient simulations, and the sliding-mesh approach. They investigate factors such as impeller-volute interaction, unsteady flow, pressure fluctuations, and the effect of viscosity and gas presence on pump performance.

The Mechanistic Modeling section focuses on developing models based on physical principles to understand ESP performance. It discusses the concept of the ideal pump head (Euler Head) and deducting head losses caused by various mechanical elements. The section mentions friction losses, shock losses, leakage losses, recirculation losses, and diffuser losses as factors affecting pump efficiency.

Overall, the literature review highlights the complexity of ESP optimization and the need for a multidisciplinary approach combining experimental research, numerical simulations, and mechanistic modeling. It identifies challenges such as understanding gas-liquid flow behavior, gas bubble dynamics, and the impact of fluid properties on ESP performance. The studies provide insights into the factors influencing ESP efficiency and suggest areas for further improvement. Some suggestions include improving the understanding of gas bubble breakup mechanisms, developing more accurate models for friction losses, and considering the effects of surfactants and viscosity on pump performance.

4.1. Experimental Studies

There are a number of hydraulic elements that affect the ESP's boost pressure, including fluid characteristics, downhole environmental conditions, and multiphase flow. In recent years, the use of ESPs in oil production systems has expanded, which has led to an increase in research into the impacts of gas entrainment and fluid viscosity.

Ippen [16] performed over 200 performance tests on four centrifugal pump versions for oil viscosities up to 10,000 SSU (Saybolt Second Universal). Comparing oil-head to water-head, braking horsepower, and effectiveness against a Reynolds-type. the dimensionless number was used to display the experimental findings. Pump boosting pressure was correlated with generic correction factors as a result of this.

Hydraulic Institute [17] for viscous liquid flow estimation using a conventional centrifugal pump with defined water performance, gave a usual experimental approach with adjustment factors. Since the Hydraulic Institute's experiments focused on a small range of pump particular speeds, Gülich (1999a, 1999b) [18, 19] and Li [20] questioned the correctness of this approach. It was discovered that extrapolation was causing unreasonable errors if the range was widened.

Stepanoff [21] used one adjustment factor Adjusted H-Q curves when water performance was known and proposed a Reynolds-type number. Gülich created a model that evaluates viscous and hydraulic frictions to calculate centrifugal pump boosting pressure. Friction losses on the disk and along the flow channel hinder centrifugal pumps' capacity to handle high-viscosity fluids. Gülich also noted that pump shape, fluid properties, and heat conditions affect friction losses.

Further experimental experiments were done by Amaral [22] and Solano [23] found There were insufficient correction factors to forecast the ESP boosting pressure from the Graphs from the Hydraulic Institute and empirical studies in the literature.

Barrios [24], Banjar [25] and others have reported inconsistent results between experimental measurement and projections based on known correlations or charts.

Solano [23] tested fluid viscosities of a seven-stage mixed-type ESP were altered by testing it with oils flowing at various temperatures. It was determined what the ESP stage-by-stage pressures would be at three different precise speed levels. Verification of the experimental results was carried out using the conservation equations of momentum and he found ESP's hydraulic head can be linked to three dimensionless variables.

Murakami [26, 27] performed the first experimental investigation on the performance of centrifugal pumps with gas entrainment. In order to observe the activity of bubbles in real-time, a transparent impeller pump was used. The pump's total head decreased as a result of the additional work required to supply air. Researchers have now carried out more experiments and numerical modeling of pump performance in case of gas flow conditions.

Experiments on the performance of ESP in gas-liquid flow circumstances have been conducted by Cirilo [28], Pessoa and Prado [29], Beltur [30], Duran [31], Zapata [32], Gamboa [33], and Salehi [34], among other, for assessing ESP performance at TUALP, Cirilo built flow loops for testing purposes. He used the tap water and air as the acting fluids to examine the water and air-water performance of 3 various forms of ESPs in relation to GVF, intake pressure, and rotational speeds. According to the findings of the study, mixed-type pumps may.
Pessoa investigated the two-phase ESP performance with an experimental 22-stage GC-6100 pump. In his research, he discovered that the average ESP behavior diverged significantly from the pressure rise measured at each level. Additionally, the borders of the Surging and Gas Locking phenomena were observed. After the initial surge in pressure, there was a second period where the slope of pressure increments against the flow rate changed once again in test curves.

Duran, Beltur, Zapata, and Salehi used the same investigational flow loop as Pessoa to undertake large experimental evaluations of ESP work in mutually liquid and gas-liquid flow regimes. Beltur looked examined how ESP running degraded in the presence of gas at various input GVFs and pressures. The input GVF is the most critical factor in ESP increasing pressure under gassy flow, according to data analysis. With GVFs above 6%, the pumping head deteriorates more quickly. Duran and Zapata created empirical correlations to forecast pressure increments through the stage and flow regimes boundaries. Zapata as well conducted further tests with a comprehensive range of rotational speeds to investigate the implications on ESP's average efficiency. Salehi conducted similar tests using a 14-stage TE-2700 ESP, looking into the effects of stage number, intake pressure, and fluid characteristics. The GVF was observed to vary stage by stage only when the ESP two-phase boosting pressure exceeded a particular threshold, under which the decline was minor plus irrespective of stage number. in summary, As GVF approached the point where downstream pump boosting pressure is better than upstream, degradation of the head pump became more apparent and stage number was impacted.

Barrios [35], Barrios and Prado [36] observed that as input GVFs rose and pump speeds fell, bubbles proliferated. ESP's ability to manage gas-liquid mixtures was negatively influenced by bubble behaviors, as seen in Fig. 3 by the association between increased bubble size and decreased pump performance. Researchers found that ESP channels with larger GVFs exhibited distinct flow patterns.

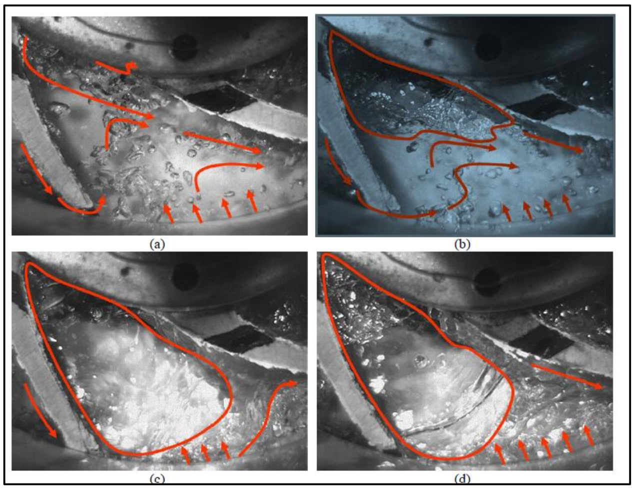

Fig. 3. Flow Via The Impeller Channel [35]

Estevam [37] and [38] classified ESP impeller flow patterns as bubbly, transition, and elongated bubble.

Gamboa [33, 13] did more complete experimental research on two-phase flow in ESP impellers. Fig. 4 shows their characteristic flow pattern map under a particular flow state. Curves denote the transition boundaries between homogeneous, bubbly, gas-pocket, and segregated flow.

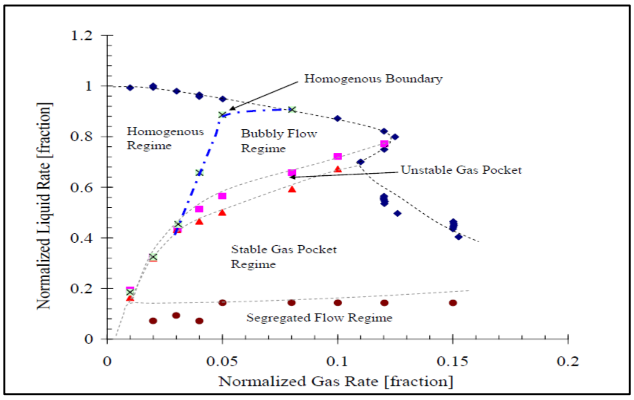

Fig. 4. Flow Patterns Map [33]

Verde, [39] used high-speed and high-resolution imagery to conduct flow pattern recognition studies inside a revolving ESP impeller. They found that the flow pattern in the impeller has a direct impact on the degree of pump performance decline. As pump performance deteriorates and operational instabilities become more prevalent, gas pocket flow patterns occur more frequently. Several technologies were suggested Schäfer [40]; Neumann [41] to understand the inner flows within a centrifugal pump; however, the researchers needed adjustments to the geometry of the pump, and their implementation was challenging. As a result, the internal flow structures had to be mounted HireCT (High-Resolution gamma-ray Computed Tomography) in order to see through the opaque pump casing or volute. To further complicate the analysis of the given experimental results Data processing using time-averaged, rotation-synchronized CT scans.

The working fluid in the ESP gas-liquid research was tap water, but the gas form was compressed air or nitrogen. Trevisan [42, 43], Banjar [25], and Paternost [44] conducted numerous recent experimental experiments concentrating on ESP gas-management capability under viscous fluid flow.

Trevisan, Trevisan and Prado Examined the influence of viscosity on liquid/gas 2-phase flow through ESP with a visualization prototype constructed from original ESP components with minimum geometric modifications. Inside the impeller channels, they discovered four liquid/air flow patterns: agglomerated bubble, segregated gas, gas pocket and intermittent gas flows. The agglomerated bubble flow was shown to be the cause of the pressure-surging trend, which is the start of pump head deterioration owing to gas entrainment. Additionally, the scientists noticed that the rise in viscosity triggered surging at significantly smaller inlet GVFs. Banjar [25] made similar findings in their experiments.

Paternost [44] studied the performance and impacts of free gas entrainment on a centrifugal pump handling single-phase viscous liquid. As liquid viscosity rose, they found that pump head degradation was being driven by the stagnation of huge gas-pocket growth.

Surfactants are hydrophobic and hydrophilic molecules that adsorb more readily at the boundary between continuous and dispersed liquids. They lower the surface tension of the continuous phase in the process [45]. However, there were few investigations on the effects of surfactants on pump performance in two-phase flow situations.

Ogata [46] experimentally measured pump head and hydraulic efficiency curves to investigate the effect of surfactant additives on centrifugal pump performance in single-phase operation. They found that when the concentration of surfactant rose, so did the pump's total head and efficiency.

Chandel [47] investigated the drag-reducing additive effect on centrifugal slurry pump performance in experimental research. The results reveal that by adding the drag-reducing additive, the pump head and efficiency improve at a rotating speed.

4.2. Numerical Simulations Studies

Computational fluid dynamics (CFD) is becoming an increasingly powerful technique for studying the performance of the pump unit in single-phase and multiphase flow settings as computer technology progresses. due to the overly complex geometries of ESP, it is challenging to explore the inner speed and pressure through an experiment. CFD, on the other hand, provides an alternative method of simulating complex interior flow configurations[48].

A centrifugal pump has a stationary volute and an impeller revolving at a predetermined angular velocity. The revolving and stationary sections of an ESP are located in the spinning and stationary computational domains in CFD, respectively.

The inner flow inside pumps, including velocity and pressure fields, can be modeled utilizing a 3D modal by CFD with the frozen-rotor interface model Asuaje, [49]; Maitelli [50]; Rajendran [51] in addition to flow recirculation and separation Cheah [52]; Zhu [53]. The frozen-rotor model is deemed a steady-state simulation because it maintains two different reference frames for the rotational and stationary components. Centrifugal pumps' dynamic flow topologies were studied using transient simulations and the sliding-mesh approach by Gonza´ Lez,[54, 55] and Huang [56, 57].

The flow of an unsteady single-phase centrifugal pump was investigated by Gonzalez et al. using numerical models that included impeller-volute contact. The impeller-volute interaction-induced unstable flow actions inside a centrifugal pump were captured by employing the sliding mesh approach to solve viscous, incompressible Navier-Stokes (N-S) equations. Numerical calculations were used to establish a relationship between global factors such as torque and impeller relative position, as well as secondary flow in the volute. The dynamic interaction between the impeller and the spiral may be accurately predicted using this method.

Using the sliding mesh technique, Huang investigated the effects of impeller and diffuser vanes on unsteady flow and pressure fluctuations. The impeller blade passing frequency was found to have a significant impact on the global variables, as validated by this investigation.

Engineers can use CFD to analyze how viscosity affects centrifugal pump performance in addition to building turbomachinery. It was found that centrifugal pumps with viscous fluids can be studied by conducting both experimental research and numerical simulation [58, 59]. Sirino [60] and Stel, [61]investigated viscosity's effect upon single-stage and 3-stage ESPs with the same pump design. In their work, they used similar computational methodologies, such as the SST turbulence model with transient rotor-stator systems. Both simulation and experiment results matched well throughout a wide-ranging of fluid viscosity.

CFD has also been used to emulate pump performance in case of gas presence, such as cavitation and free-gas entrainment flow.

Barrios [35, 62] performed multiphase CFD simulations on a single-stage ESP impeller using unique models of bubble size and drag coefficient predictions. Their theories matched experimentally observed streamlines and gas-accumulation zones.

Qi [63] developed ESPs with the high-level-temperature gas-liquid 2-phase flow for geothermal applications. The planned mix-type centrifugal impeller and diffuser were adjusted for better gas handling and higher efficiency across a wide range of production rates using CFD simulations.

Zhu and Zhang [64] conducted 3-stage ESP simulations with an impeller and a diffuser in each step using multiphase CFD. Comparing their findings to experimental observations, it was clear that bubble size played a significant role in ESP performance under gaseous conditions.

Changes in local pressure, variations in gas void percentages, and bubble breakup or coalescence are examples of transient multiphase flow events in ESP. To more accurately simulate the hydrodynamics of gas-liquid two-phase flow in a rotating centrifugal pump, unstable CFD simulation code should be combined with a multiphase flow model and transient rotor-stator approach to account for impeller and diffuser interactions. On the other hand, transient CFD simulations have a much larger computational cost than steady-state simulations.

4.3. Mechanistic Modeling

After deducting head losses owing to several mechanical losses elements such as (Friction, shock, leakage, recirculation, diffuser, and disk), the efficient and ideal pump head can be defined as Euler Head (H E), as indicated in Equation:

$$\mathbf{H = HE - H_{friction} - H_{shock} - H_{leakage} - H_{recirculation} - H_{diffuser} - H_{disk}} \quad (1)$$

Where: $H_{friction}$: Losses because of fluid friction in the impeller, H_{shock} : Losses when changing the flowrate from the design rate, $H_{leakage}$: Losses between rotating and stationary parts, $H_{recirculation}$: Losses from the shaft due to pressure gradient, $H_{diffuser}$: Losses due to the friction on diffuser walls, H_{disk} : Losses due to rotating disk and fluid.

Where each factor was discussed and researched by several researchers as will be summarized in Tables.

The friction losses in the interior pump impeller are summarized in Table 1. According to Takacs (2009), friction losses rise with liquid rate and are caused by fluid friction in the impeller.

Table 1. Models of Friction Loss in the Literature

References	Models
Macaluso [65] (Sun and Prado [66] thin[67]	$h_{friction} = b_2 \frac{(D_2 - D_1)(W_1 + W_2)^2}{8gsin\beta_2 rH}$
Ito [68] Churchill [69] (Sun and Prado [66]	$h_{friction} = \frac{f_{\gamma\beta\omega} Q^2}{8gD_H \pi^2 b_m^2 sin^3\beta_m}$
Ito¯ and Nanbu [70] Bing, Tan [71]	$h_{friction} = N_a f_{\gamma\beta\omega} \frac{s}{D_H} \frac{W_1^2 + W_2^2}{4g}$
Zhu [15]	$h_{friction} = f_{FI} \frac{V_1^2 L_1}{2gD_1}$

Shock losses in centrifugal pumps have not been widely studied in the past since they are insignificant at the best efficiency point BEP. As seen in Table 2, there are just a few empirical relationships available.

Table 2. Models of Shock Losses in the Literature

References	Models
Stepanoff [21] Amaral [72] Thin [67]	$h_{shock} = k_{shock}(Q - Q_{BEP})^2$
Sun and Prado [66] Macaluso [65] Thin [67]	$h_{shock} = \frac{k_{shock}}{2g}(\frac{Q - Q_{BEP}}{Q_{BEP}} u_1)^2$
Zhu [15]	$h_{TI} = f_{TI} \frac{V_1^2}{2g}$

According to Tackas (2009), leakage losses, which are losses caused by clearances between spinning and immobile sections of the pump stage (at the impeller eye, through balance holes, and so on), decrease as liquid rates rise. Similar empirical equations for calculating leakage loss were proposed by Aungier [73] and Bing [71]:

$$h_{leakage} = Q_{c1} \frac{Q_{c1} u_{c1} u_2}{2Qg} \quad (2)$$

Where Q_{c1} is the leaking fluid volume, U_{c1} is the leakage fluid velocity, and Q is the pump's optimum flow rate.

Loss of recirculation occurs in a rotating centrifugal pump due to squandered fluid energy that continuously emerges from the shaft due to an unfavourable pressure slope from the impeller input to output. The unfavourable pressure gradient grows as the liquid flow rate declines, resulting in more severe head loss due to fluid recirculation (Table 3).

Table 3. Models of Recirculation Loss in Literature

References	Models
Tuzson [75] Gülich [18]	$h_{recirculation} = \frac{C_2^2 - C_{2E}^2}{2g}$

The researches [66, 76] asserted that diffuser loss is primarily driven by friction on the diffuser walls. Table 4 shows the diffuser loss calculation methods that were used in the prediction models. The majority of the equations are the same as the friction loss formulas in Table 1.

Table 4. Models Diffuser Loss in the Literature

References	Models
Ito [68, 70] Churchill [69] Shah [77] Sun and Prado [78]	$h_{diffuser} = -\frac{F_\gamma F_\beta f Q^2}{8 g D_H \pi^2 b_m^2 sin^3 \beta_m} \frac{r_{3dif} - r_{2dif}}{r_{3dif} r_{2dif}}$
Bing [71] Shah [77]	$h_{diffuser} = N_a (F_\gamma F_\beta f) \frac{S}{D_H} \frac{(V_{2d}^2 + V_3^2)}{4g}$
Amaral [22] Ladouani and Nemdili [79]	$h_{diffuser} = \frac{(V_{2d}^2 - V_3^2)}{2g} - C_p \frac{V_3^2}{2g}$; $C_p = \frac{(p_3 - p_2)}{0.5 \rho V_3^2}$ $V_{2d} = \frac{Q}{\pi (r_{2diff}^2 - r_{1diff}^2)}$; $V_3 = V_1$

Stepanoff [21] identified disk friction losses as the result of contact between a rotating disk and fluid. As a result of the viscous shear forces acting on the disk surfaces, more power is spent to keep the disk moving (Table 5).

Table 5. Models Disk Friction Losses in the Literature

References	Models
Sun and Prado [66] Amaral [22]	$h_{disk} = \frac{(V'^2_2 - V_{2d}^2)_{BEP}}{2g}$
Thin [67]	$h_{disk} = \frac{f_{disk} \rho \omega^3 r_2^5}{10^9 Q}$
Van Esch [80]	$h_{disk} = \frac{c_m \omega^3 r_2^5}{2gQ}$

c_m is an empirical constant

4.4. Production Optimization Studies

The main takeaway from the provided information is that optimizing the performance of a large oilfield with numerous ESP-boosted wells in a complex production network is a challenging task. Production engineers need to make decisions regarding the adjustment of individual ESP frequencies and the shut-in of high water-producing wells to optimize the production system. The use of historical and real-time data, along with modeling and mathematical optimization techniques, plays a crucial role in diagnosing and optimizing the functioning of ESP-lifted wells.

Controlling and optimizing the performance of a huge oilfield with hundreds of ESP (Electric Submersible Pump)-boosted wells placed in a wide production network can be a very tough task. On a daily/ weekly basis, production engineers have to make decisions on (1) the update of individual ESP frequencies and (2) the shut-in of high water-producing wells. the optimization of production systems in the oil and gas industry with practical operating constraints has gotten a lot of attention, as evidenced by various publications. Bates [81] highlight the use of historical and real-time data during startup, operation, and shutdown to diagnose and optimize the functioning of ESP-lifted wells, as well as modeling. Castro [82] and Takacs [83] explain the advantages of revising pump design to enhance ESP performance Stanko and Golan [84] and Stanko [85] designed and deployed a model-based advice system to support the production management of the Rubiales field. The method involves applying mathematical optimization techniques to a "canned" commercial software-based numerical model of a production network. The network model accurately replicates the actual production system in its current condition (e.g., tuned to and containing field data). The model computes the rates, pressures, and temperatures along the system, assuming pseudo-steady state inflow deliverability. The optimization is designed to increase oil production or economic revenue by altering ESP frequencies while concurrently meeting several operational constraints.

Generally, ESP Optimization algorithms (Table 6) are procedures designed to use many parameters from producing well (Completion dimension, ESP equipment dimension, real-time operating parameters dimension) to get a new set of operating conditions that will be the best fits and the desired target function whether it is maximum production, maximum pump efficiency, or others. Depending on the specific case.

To achieve successful optimization, it is critical to consider factors such as historical and real-time data analysis, modeling, diagnostic procedures, and the application of mathematical optimization techniques. Furthermore, leveraging AI, machine learning, and digital monitoring systems can greatly enhance the efficiency and effectiveness of ESP optimization.

For further improvement, it could be beneficial to explore the integration of advanced technologies such as advanced data analytics, real-time optimization algorithms, and automation. Additionally, researching and implementing predictive maintenance solutions can help reduce downtime and improve the overall reliability of ESP systems. Continuous research and development in the field of ESP optimization, incorporating the latest advancements in technology, can lead to further improvements in oilfield production efficiency and performance.

Table 6. Production Optimization in Literature

References	Application
Al-Jasmi [86]	Study ESP Smart Flow Combines Quality and Control Data in Real Time for Diagnostics and Optimization
Adesanwo [87]	Investigate Intelligent Surveillance of Electrical Submersible Pump Systems Using Smart Alarming
Shuwaikhat [88]	They created an improved approach and monitoring system that combines all ESP parameters and factors onto a single platform. A diagnostic procedure, production optimization, ESP track and trip prediction alarm, ESP dashboard with production rates, and field overview are all capabilities of the system that can be used to determine quick remedial action. This method operates as a quality assurance system, employing computational models to forecast ESP trips or failures in advance.
Jansen van Rensburg [89]	They talked about how AI could be used to develop a predictive maintenance system for ESPs. Also presented is how to deploy an autonomous surveillance solution for ESP systems utilizing the predictive maintenance solution, and how to do so using artificial intelligence AI technology in conjunction with a cloud-based Internet of Things IoT platform.
Jansen Van Rensburg and Kamin [90]	Predictive Models Based on Machine Learning to Enable Preventative Maintenance and Prevent ESP Downtime.
Sanusi [91]	They Use Machine Learning to build models that can be used to forecast pump intake pressure PIP when it is not available or to confirm gauge readings when they are suspicious. Using RSM and ANN, an empirical equation for predicting PIP was established and then optimized.
Diker [92]	Based on data from the Mittelplate oil field, Wintershall Dea is creating a digital system with partners to monitor and optimize electrical submersible pump (ESP) performance. This technology uses machine learning (ML) models that are fed by historical data to alert engineers and operators when operating conditions are drifting outside of the operating envelope, allowing them to avoid potential performance issues.
Bermudez [93]	By using Intelligent Maximum Production (IMP) algorithm the could maximize production from tight oil wells during the first high-output stage, as well as prevention of gas-locking as gas production increases later.

5- Conclusions

The main objective of this study is to deliver a general review of the development of the ESP Optimization problem and the available studies and applications to solve the problem at hand. After reviewing a fair number of studies and papers on the problem of ESP Optimization the following conclusions were made:

1- The solutions available for the ESP optimization problem were evolved rationally with the rising computational power and the computer abilities that were available to be utilized to the solution of the problem.
2- The availability of the ESP data and their amount plays a major part in the selection of the optimization technique that will be used for the task and the degree of accuracy that will be a result of this technique.
3- In the literature, there are studies of centrifugal pump performance under gassy flow. However, the gas bubble behavior and its impact on two-phase flow hydrodynamics in rotating ESPs are still a mystery.
4- The surfactant effect was not taken into account in the majority of ESP pressure-boosting experiments. Under gassy flow conditions with different amounts of surfactants, extensive experimental evaluations of ESP stage pressure increment should be done.
5- It is highly challenging to see ESP interior flow structures and bubble movement when the impeller is rotating because of the small and complex geometry.
6- CFD simulations can provide detailed information of flow structures inside the impeller.
7- More attention was made to forecasting pump performance in two-phase systems rather than flow structures inside ESPs in previous numerical simulation studies.
8- Mechanistic modeling of ESP two-phase performance is still preliminary in the literature. Experimental investigations are insufficient on ESP two-phase flow behaviors including flow patterns and transition boundaries. The development and

validations are also critical for the accuracy of mechanistic model predictions.

Nomenclature

AI	Artificial-Intelligence
ALS	Artificial Lift Selection
BEP	Best Efficiency Point on the pump curve
BFPD	Barrels of fluid per day
DHT	Downhole Tool/ Gauge
FVF/Bo	Formation Volume Factor
GVF	gas volumetric fraction
GOR	Gas to Oil Ratio
KVA	Kilo-volt Ampere (Power Capacity/ Requirement)
NLAP	Net Lift above Pump
PI	Productivity Index
Pi	Intake/ Annulus Pressure
Pd	Discharge Pressure
QC	Quality Control
Re	Reynolds number
TUALP	Tulsa University Artificial Lift Projects
Ti	Intake/ Annulus temperature
Tm	Motor Temperature
ROR	Recommended Operating Range
WHP	Well Head Pressure/ Tubing Pressure
GA	Genetic-Algorithm
IPR	Inflow Performance Relationship
MINLP	Mixed-Integer-Non-Linear-Programing
STB	Stock Tank Barrel
VSD	Variable Speed Drive

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مراجعة التسلسل الزمني لتطوير المضخات الغاطسة الكهربائية

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الخلاصة

تعتبر المضخة الغاطسة الكهربائية الغاطسة المعروفة باسم (ESP) من أبرز حلول الرفع الاصطناعي في هندسة الإنتاج؛ نظرًا لكمية إنتاجها الأكبر مقارنة بطرق الرفع الاصطناعية الأخرى حيث يعمل المرساب الكهروستاتيكي على زيادة الانتاج من خلال تحويل الطاقة الحركية إلى ضغط هيدروليكي للسائل. طرق تحسين ادائية المضخة الغاطسة معقدة بسبب الحاجة إلى التعامل مع عدد كبير من الوظائف والقيود، على سبيل المثال: (تقييد التدفق الداخلي، وجزء فراغ الغاز عند الشفط، وتقييد التدفق الخارجي، مكونات المضخة والقيود الكهربائية والميكانيكية). نظرًا لأهميتها وكفاءتها الكبيرة، من الضروري فهم كيفية ظهورها وكيف تطورت بمرور الوقت، فضلاً عن التحديات التي واجهتها في الصناعة النفطية. تقدم هذه الورقة مراجعة شاملة لأصل ESP والدراسات التطورية السابقة تضمنت مراجعة لجميع الدراسات السابقة التي أثرت على تطوير المضخة الغاطسة، بما في ذلك مكوناتها الكهربائية والميكانيكية ، وكذلك جميع مكونات قاع البئر والسطح. تم تقسيم مراجعة الأدبيات إلى أربعة أقسام: الدراسات التجريبية، ودراسات المحاكاة العددية، والنمذجة الميكانيكية، والدراسات المتعمقة حول تحسين الإنتاج.

الكلمات الدالة: مضخة كهربائية غاطسة، رفع اصطناعي، تحسين الأنتاج.