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A critical analysis and improvements of empirical models for predicting the performance of Electrical Submersible Pumps under viscous flow

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ABSTRACT

One of the main challenges associated with Electrical Submersible Pumps (ESPs) system is the correct sizing of the pump. High viscosity fluids, emulsions, or compressible fluids significantly impact the pump's ability to transfer energy to the fluid. Obtaining ESP characteristic curves in conditions resembling real applications is complex but essential for the correct design, operation, optimization, and safeguarding of ESP systems. The objective of this study is to critical assess the traditional methods for predicting the ESP performance under viscous flow. This study also improves these methods driven by ESP performance data. The results show that the original models have limitations because their databases are primarily based on data from conventional centrifugal pumps. Consequently, using these methods can result in significant errors in the sizing of the production system. The accuracy of the models improved significantly after modifying the methods. Reductions in errors were observed in all correction factors, and particularly in the prediction of global performance. The improvements were effective in mitigating the effects of increased deviations with the reduction in Reynolds number observed when applying the original models to predict flow rate and efficiency.

1. Introduction

Oil production from non-naturally flowing wells or those with low and uneconomical flow rates represents a complex engineering challenge. In such scenarios, artificial lift methods prove indispensable for production. The Electrical Submersible Pumping (ESP) system is an artificial lift method used for this purpose. This technology can be used in conventional or unconventional mature fields, thermal recovery, and deepwater offshore wells. One of the key advantages of the ESP system is its flexibility, including a wide range of flow rates and lifting capacities, different completion types, and recent innovations such as the ESP skid and MoBo (Colodette et al., 2008; Costa et al., 2013).

One main component of the ESP system is the multistage centrifugal pump. These turbomachines are responsible for converting the power received from the electric motor into hydraulic energy for lifting the oil. In this equipment, energy is continuously transferred to the flowing fluid through the dynamic action of moving blades. Similar to all centrifugal pumps, the properties of the pumped fluid directly influence the dynamic energy transfer process. In simple terms, any difference from pure water properties can greatly affect the ESP's performance and operational stability. However, the rheological characteristics of fluids, as well as the flow dynamics in field application, significantly deviate from ideal operating condition for ESP systems. Generally, ESPs encounter challenges with two-phase flows (gas–liquid and liquid–liquid), three-phase flows (gas–liquid–liquid), emulsions, high viscosity mixtures, and abrasive solids (Monte Verde et al., 2021; Bulgarelli et al., 2017).

These common scenarios for ESPs lead to the main hydraulic challenges associated with the equipment. Obtaining ESP characteristic curves in conditions close to the real application is complex but essential for the correct design, operation, optimization, and safeguarding of the ESP systems. Usually, manufacturers provide characteristic curves for head, Brake horsepower (BHP), and efficiency based on operation with water. Deviations from these conditions are taken into account by adjusting these reference curves with different methods. A usual correction is made to account for the oil viscosity, which is a fundamental step in pump sizing. Furthermore, obtaining the viscous performance of ESPs is imperative in applications where the pump is utilized for production allocation, as is the case of Peregrino field, Campos Basin, Brazil (Olsen et al., 2011).

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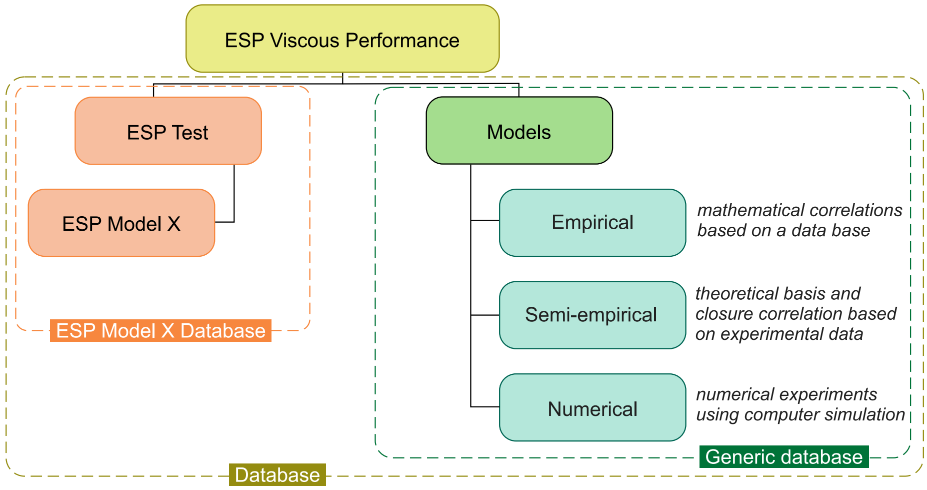

Fig. 1. Approaches for determining the performance of ESPs operating with viscous fluids.

The methodologies used to obtain the viscous performance of ESPs can be divided into two categories, as shown in Fig. 1. The first is to effectively test the ESP with the desired viscosity, determine its performance, and obtain the characteristic curves. From these results, dedicated empirical models are developed for representing the pump performance in viscosities and speeds different from those tested. This methodology is highly precise, with its accuracy influenced only by experimental uncertainties and interpolations for conditions out of the test matrix. However, this approach has the drawback of increased cost and time, as it involves a complex and unusual procedure, since the standard test is performed by manufacturers using water. In addition, few facilities have the suitable infrastructure to carry out this type of testing, meaning that not even manufacturers have the viscous characterization of all pumps in their catalog.

The second procedure involves using models to estimate performance degradation. In this methodology, a database is used and models are proposed to predict the performance of a pump that is not necessarily part of this database. These models can be empirical, semi-empirical or the result of numerical simulation. In general, empirical models are independent of a rigorous physical basis, originating from correlations obtained through mathematical fittings. Thus, an empirical correlation is essentially a mathematical representation of the experimentally observed dependence between its variables. Usually, the empirical models require minimal information about the pump's geometry and are simple to apply, involving only analytical correlations.

On the other hand, the semi-empirical models have theoretical basis and employ closure correlation based on experimental data. This approach requires a higher level of geometry detail compared to the empirical approach. Finally, numerical models use Computational Fluid Dynamics (CFD) to simulate a specific pump geometry and provide performance curves. This approach requires complete equipment geometry, which can often be challenging to obtain. This methodology also requires specialized simulation software, which involves skilled labor and substantial computational costs.

In this study, the empirical approach was chosen. This choice was made because these models do not require geometric detailing of the pump, which is often restricted data and difficult to obtain. In addition, the ease of implementing empirical models in simulators and dimensioning software through User Defined Functions (UDF) contributes to their widespread acceptance in the oil industry.

The present work is a continuation of the research presented by Monte Verde et al. (2023), where the authors conducted an extensive experimental work that supports the present study. The objectives are to provide a critical analysis and propose improvements for the empirical models proposed by Stepanoff (1949)/TUALP (2006), KSB (1989), Gülich (2008), ANSI-HI (2010), Monte Verde (2016), and Ofuchi et al. (2020) for predicting the ESP performance under viscous fluid flow. For this purpose, the experimental database of ESP performance presented by Monte Verde et al. (2023) was used as a benchmark. The evaluation of these empirical models was carried out using performance metrics, which quantify the difference between the predicted values by the models and the measured values of the database. To modify and improve these empirical models, the database available for ESPs was used and the empirical constants of the models were optimized and recalculated to minimize the error of the viscous performance prediction.

The main contribution of this work is to quantify the accuracy of traditional methods in predicting the ESPs performance. This analysis is particularly relevant as most of these methodologies were originally developed for volute pumps, which differ from multi-stage centrifugal pumps used in ESP systems. Another significant contribution of this study is the optimization of these methods driven by ESP performance data. This optimization modifies the models specifically for ESPs, leading to a substantial improvement in the predictive ability of the methods.

2. Literature review

Methodologies with empirical approach generally use correction factors to estimate the viscous performance of centrifugal pumps. These dimensionless parameters provide the performance degradation and are a function of the characteristics in water (w subscript) and viscous (vis subscript) services. The flow rate (C_Q), head (C_H) and efficiency (C_η) correction factors are defined as:

$$C_Q = \frac{Q_{vis}}{Q_w} \tag{1}$$

$$C_H = \frac{H_{vis}}{H_w} \tag{2}$$

$$C_\eta = \frac{\eta_{vis}}{\eta_w} \tag{3}$$

where Q is the flow rate, H is the head, and η is the efficiency.

In the next section, the empirical methods proposed by Stepanoff (1949)/TUALP (2006), KSB (1989), Gülich (2008), ANSI-HI (2010), Monte Verde (2016) and Ofuchi et al. (2020) are detailed. These are the methods that were assessed and modified in the present work.

Stepanoff (1949)/TUALP (2006). Based on experimental results from sixteen volute centrifugal pumps with dimensionless specific speed between $0.283 < \omega_s < 0.724$ and kinematic viscosity up to 2020 mm^2/s, Stepanoff (1949) proposed a traditional procedure widely used in the industry. The main hypothesis of the model assumes that, at a constant speed, the pump head decreases as the viscosity increases, in such way that the specific speed (ω_s) at Best Efficiency Point (BEP) remains constant:

$$\omega_s = \frac{\omega\sqrt{Q_{w,BEP}}}{\left(gH_{w,BEP}\right)^{3/4}} = \frac{\omega\sqrt{Q_{vis,BEP}}}{\left(gH_{vis,BEP}\right)^{3/4}} \tag{4}$$

where ω is the rotational speed in rad/s, Q is the flow rate in m^3/s, and H is the pump head in m.

From Eq. (4) a generalization yields:

$$C_{Q,BEP} = C_{H,BEP}^{a} \tag{5}$$

where a is a dimensionless constant shown in Appendix.

The author proposed an abacus that provides $C_{H,BEP}$ as a function of Stepanoff's Reynolds number. This parameter depends on the flow rate in viscous service, which is unknown, making the correction procedure iterative. TUALP (2006), apud (Solano, 2009), proposed modifications to Stepanoff's methodology to make the procedure non-iterative. The modified methodology is based on a Reynolds number ($Re_{evdocia}$) that is only a function of the pump's performance in water service, defined as:

$$Re_{evdocia} = 6.0345\frac{\omega Q_{w,BEP}}{\nu\sqrt{H_{w,BEP}}} \tag{6}$$

where ω is the rotational speed in rpm, $Q_{w,BEP}$ is the water flow rate at BEP in bdp, ν is the kinematic viscosity in cSt, and $H_{w,BEP}$ is the pump head at BEP in ft.

Using the modified Reynolds number, the authors reconstructed Stepanoff's abacus and provided an analytical expression for calculating $C_{H,BEP}$:

$$C_{H,BEP} = 1 - e^{\left(-bRe_{evdocia}^{c}\right)} \tag{7}$$

where b and c are empirical dimensionless constants shown in Appendix.

Once the $C_{H,BEP}$ is calculated, $C_{Q,BEP}$ is obtained by Eq. (5) and the performance is estimated by applying Eqs. (1) and (2). The procedure of Stepanoff (1949)/TUALP (2006) is applicable only for the BEP and does not predict the efficiency or brake horsepower (BHP) in the viscous service.

KSB (1989, apud Gülich, 2008). KSB proposed abacuses and correlations for performance predictions that consider the pump's specific speed. These abacuses were developed for single-stage centrifugal pumps, with specific speed between $0.113 < \omega_s < 0.849$ and kinematic viscosity up to 4000 mm^2/s.

This methodology is based on the dimensionless parameter B_{HI} calculated at BEP with water, defined by:

$$B_{HI} = \frac{480\left(\nu\right)^{0.5}}{\left(Q_{w,BEP}\right)^{0.25}\left(gH_{w,BEP}\right)^{0.125}} \tag{8}$$

where all variables are in the SI units, i.e. $[\nu]$ is m^2/s, $[Q_{BEP}]$ is m^3/s, $[H_{BEP}]$ is m, and g is the gravity acceleration in m/s^2.

The parameter B_{HI} is modified as a function of the specific speed and yields the B parameter:

$$B = B_{HI}\sqrt{\frac{a}{52.933\omega_s}} \tag{9}$$

where ω_s is defined by Eq. (4) for water service.

The flow rate and head correction factors applicable for the BEP and other flow rates are given by:

$$C_Q = \left(\frac{a}{52.933\omega_s}\right)^{b.B} e^{-c\left(log_{10}B\right)^d} \tag{10}$$

$$C_H = \left(e + f.C_Q\right)\xi \tag{11}$$

where:

$$\xi = 1 - 0.014\left(B_{HI} - 1\right)\left[\left(\frac{Q_w}{Q_{w,BEP}}\right) - 1\right] \tag{12}$$

The efficiency correction factor is given by:

$$C_\eta = B^{-\beta} - \Delta n_Q \tag{13}$$

where:

$$\beta = g.B^h \tag{14}$$

and:

$$\Delta n_Q = \begin{cases} i\left(25 - 52.933\omega_s\right), & \text{for } \omega_s < 0.472 \\ i\left(52.933\omega_s - 30\right), & \text{for } \omega_s > 0.567 \end{cases} \tag{15}$$

where coefficients $a, b, \dots, i$, shown in Appendix, are empirical constants.

Therefore, the KSB method is valid for the BEP and other flow rates. As per the method, C_Q and C_η are independent of the operating condition, while C_H depends on the operating flow rate.

Gülich (2008). The author proposed a prediction procedure based on test results available in the literature and semi-empirical energy loss models (Gülich, 1999a,b). This methodology is valid for viscosities up to 4000 mm^2/s and specific speed between $0.132 < \omega_s < 0.936$. The correction factors are functions of the dimensionless parameter $Re_{Gülich}$ defined as:

$$Re_{Gülich} = Re_\omega \omega_s^a \tag{16}$$

where Re_ω is the dimensionless rotational Reynolds number, given as:

$$Re_\omega = \frac{\omega r_2^2}{\nu} \tag{17}$$

and r_2 is the impeller outer diameter.

The head correction factor at the BEP is given by:

$$C_{H,BEP} = Re_{Gülich}^{x} \tag{18}$$

where x is defined by:

$$x = -\left(\frac{b}{Re_{Gülich}^{c}}\right) \tag{19}$$

For flow rates different from BEP, the head correction factors are calculated by:

$$C_H = 1 - \left(1 - C_{H,BEP}\right)\left(\frac{Q_w}{Q_{w,BEP}}\right)^{0.75} \tag{20}$$

Gülich (2008) assumes that the flow rate correction factor, valid at BEP and other flow rates, is equal to the head correction factor at BEP, which is:

$$C_Q = C_{H,BEP} \tag{21}$$

The efficiency correction factor is also a function of the $Re_{Gülich}$:

$$C_\eta = Re_{Gülich}^{y} \tag{22}$$

where y is calculated by:

$$y = -\left(\frac{d}{Re_{Gülich}^{e}}\right) \tag{23}$$

where coefficients $a, b, \dots, e$, also shown in Appendix, are empirical constants.

Similar to the KSB (1989) method, the methodology proposed by Gülich (2008) is valid for the BEP and other flow rates and assumes that C_Q and C_η are independent of the operating condition, while C_H depends on the operating flow rate.

ANSI-HI 9.6.7 (2010). This is the procedure provided by the Hydraulic Institute for predicting the performance of centrifugal pumps operating with viscous fluid. The proposed methodology consists of an empirical model based on an extensive database for different pump geometries. The procedure is valid for $\omega_s < 1.097$ and kinematic viscosity up to 4000 $\mathrm{mm^2/s}$. For copyright reasons, only the functional relationships are presented for the ANSI-HI (2010) procedure, and the complete equations are omitted.

The correction factors are functions of the independent parameter B:

$$B = f_1\left(\nu, H_{w,BEP}, Q_{w,BEP}, \omega, a, b, c, d\right) \tag{24}$$

$$C_{H,BEP} = f_2\left(B, e, f, g\right) \tag{25}$$

$$C_H = f_3\left(C_{H,BEP}, Q_w, Q_{w,BEP}\right) \tag{26}$$

$$C_\eta = f_4\left(B, h, i\right) \tag{27}$$

where coefficients $a, b, \ldots, i$ also shown in Appendix, are empirical constants.

Similar to Gülich (2008), the ANSI-HI (2010) methodology assumes that flow rate correction factor, valid at BEP and other flow rates, is equal to the head correction factor at BEP, as shown by Eq. (21). Furthermore, similar to KSB (1989) and Gülich (2008), the ANSI-HI methodology assumes that C_Q and C_η are independent of the operating condition, while C_H depends on the operating flow rate.

Monte Verde (2016). The author proposed an empirical model for performance prediction based on the experimental data from a three-stage ESP, model GN5200, operating between 1800 and 3500 rpm, and dynamic viscosity up to 1069 $\mathrm{mm^2/s}$. The procedure is based on Gülich's model, however independent correlations were proposed for the head, flow rate, and efficiency.

The head and efficiency correction factors at BEP are calculated by Eq. (18) and (22), respectively, where x and y are defined as:

$$x = -\left(\frac{b}{Re^{c}_{Gülich}}\right) \tag{28}$$

$$y = -\left(\frac{d}{Re^{e}_{Gülich}}\right) \tag{29}$$

The flow rate correction factor at BEP is given by:

$$C_{Q,BEP} = Re^{z}_{Gülich} \tag{30}$$

where z is:

$$z = -\left(\frac{f}{Re^{g}_{Gülich}}\right) \tag{31}$$

where coefficients $a, b, \ldots, g$ also shown in Appendix, are empirical constants.

The correlations proposed by Monte Verde (2016) are limited to the BEP condition and recommend to $600 < Re_{\omega_s} < 10^6$.

Ofuchi et al. (2020). The authors proposed hybrid correlations based on the experimental results presented by Amaral et al. (2009) for the ESP GN7000 and results from numerical simulations of two other ESPs provided by Ofuchi et al. (2017). The methodology is based on Ofuchi Reynolds number (Re_{Ofuchi}), a dimensionless number defined as:

$$Re_{Ofuchi} = \frac{\omega_v Q_{w,BEP}}{\nu\sqrt{g H_{w,BEP}}}\frac{1}{\omega_{s,op}} \tag{32}$$

where ω_v is the rotational speed during viscous operation and $\omega_{s,op}$ is the dimensionless operational specific speed given by:

$$\omega_{s,op} = \frac{\omega Q_{op}^{1/2}}{\left(g H_{op}\right)^{3/4}} \tag{33}$$

where ω is the rotational speed that provides $Q_{w,BEP}$ and $H_{w,BEP}$ in Eq. (32), as the subscript *op* represents any operational condition from the water curve, which will be degraded to viscous operation.

The correlation fitted for the head correction factor is:

$$C_H = Re^{x}_{Ofuchi} \tag{34}$$

where:

$$x = -\left(\frac{b}{Re^{c}_{Ofuchi}}\right) \tag{35}$$

where the constants a, b, and c are shown in Appendix.

The authors assumed the same hypothesis of Stepanoff (1949), so C_Q is calculated by Eq. (5). The procedure presented by Ofuchi et al. (2020) is applicable for the BEP and other flow rates, but it does not provide predictions for efficiency or BHP.

3. Methodology

This section presents the methodology used to assess the empirical models and, subsequently, modify them using an ESP database. The methodologies are based on statistical parameters, as well as on non-linear optimization models, which are detailed in the following sections.

3.1. Assessment of empirical models for predicting ESP performance

The evaluation of the empirical models was carried out by comparing the correction factors obtained experimentally and those calculated by the models. Empirical correction factors are provided by Monte Verde et al. (2023). In our previous work, we presented a database comprising six centrifugal stages commonly used in ESP systems: P37, P47, P62, P100, HC10000, and HC12500. All tested ESPs were three-stage pumps. These models operated at four rotational speeds (1800, 2400, 3000 and 3500 rpm) and twelve viscosities (1 to 1273 mPa s or 1 to 1020 $\mathrm{mm^2/s}$), resulting in a comprehensive database of over 5800 operating conditions. The models evaluated in the present study are: Stepanoff (1949)/TUALP (2006), KSB (1989), Gülich (2008), ANSI-HI (2010), Monte Verde (2016), and Ofuchi et al. (2020).

Giving a dataset of experimental correction factors $y_i = y_1, y_2, \ldots, y_n$ and a dataset of predicted correction factors $\hat{y}_i = \hat{y}_1, \hat{y}_2, \ldots, \hat{y}_n$, the accuracy of the prediction for a specified condition $\Gamma_i = (y_i, \hat{y}_i)$ can be quantified by the absolute relative error (e_r):

$$e_r = \frac{\left|\hat{y}_i - y_i\right|}{y_i}.100 \tag{36}$$

and, when $\Gamma_i = (y_i, \hat{y}_i)$ is a vector, the quality of the prediction can be calculated in different ways, such as by mean absolute percentage error (MAPE), root mean squared error (RMSE), and coefficient of determination (R^2):

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\frac{\left|\hat{y}_i - y_i\right|}{y_i}.100 \tag{37}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\hat{y}_i - y_i\right)^2} \tag{38}$$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(y_i - \hat{y}_i\right)^2}{\sum_{i=1}^{n}\left(y_i - \bar{y}_i\right)^2} \tag{39}$$

where $\bar{y}_i$ is the mean of a sample with n measured data. Each statistical parameter provides different information and must be analyzed together.

3.2. Improvements of empirical models for predicting ESP performance

Since the empirical models in the literature are primarily based on conventional centrifugal pumps or limited ESP geometries, we propose

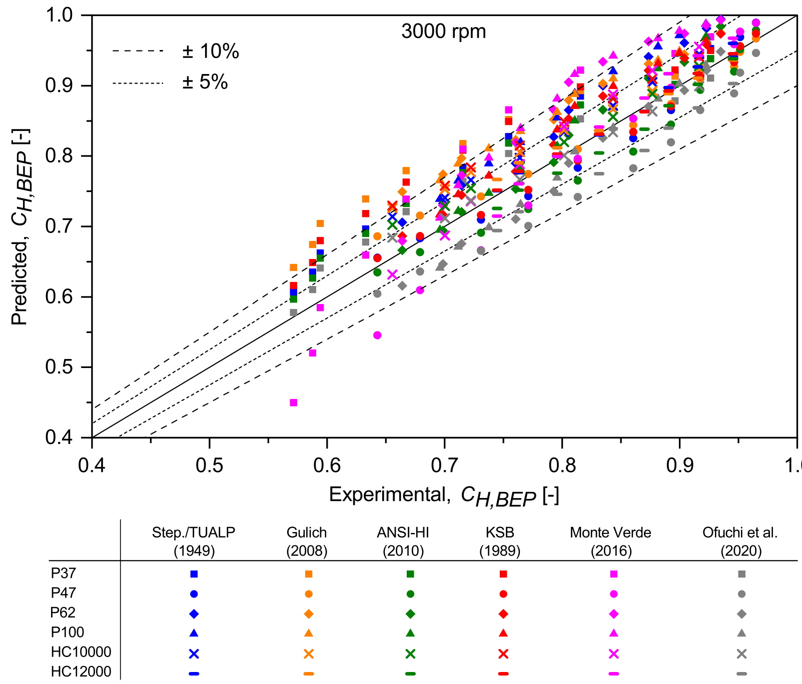

Fig. 2. Comparison between the measured and predicted head correction factor at BEP for different ESP models at 3000 rpm.

optimizing these methods using a performance database specific to ESPs. The methodology consists of modifying the original empirical coefficients while considering the database provided by Monte Verde et al. (2023). The functional form of the models remains unchanged and only the empirical coefficients are modified. This modification involves substituting the original database, which was used by the authors during the development of their methods, with the specific database for ESPs. The optimization is carried out only for the BEP since not all methods provide predictions for other operational conditions.

In addition, simultaneous optimization of all constants of each model was performed. This approach aims to minimize errors in predicting the three correction factors, preventing the model from excelling in predicting a single factor at the expense of producing unsatisfactory results for the other factors. This approach ensures a more balanced and comprehensive prediction. The optimization of the coefficients was executed using the Levenberg–Marquardt method. The original constants of each model were employed as the initial estimate for the adjusted parameters. The optimization of each model was carried out by minimizing the global RMSE of the model for the BEP point.

4. Results

4.1. Assessment of empirical models

Fig. 2 shows the comparison between the head correction factors measured at BEP and those predicted by the methods, for different ESP models at 3000 rpm. In general, the empirical models provide reasonable predictions for the ESP head operating with viscous fluid. At 3000 rpm, approximately 89% of the predicted points fall within the ±10% range. The model proposed by ANSI-HI (2010) stands out, with approximately ±98% of the predicted head points falling within the ±10% range, and ±72% of them exhibiting deviations of less than ±5% from the measured value. The model proposed by Ofuchi et al. (2020) tends to overestimate head degradation, i.e. it predicts a lower head than the measured value. In contrast, the Stepanoff (1949)/TUALP (2006), Gülich (2008), and KSB (1989) models tend to underestimate performance degradation by predicting a head greater than the experimental measurement.

Table 1 shows the statistical evaluation of the head predicted by empirical models, providing a comprehensive view of the models' behavior for the entire database and the observed deviations for each ESP model. The statistical parameters affirm the robust performance of the (ANSI-HI, 2010) procedure in predicting head, as indicated by the following metrics: MAPE ranging from only 1.9% to 7.9%, maximum error between 5.7% and 14.6%, RMSE values between 0.018 and 0.055, and R^2 ranging from 0.614 to 0.959. This method provides suitable results for all ESP models, with emphasis on the P62, P100, and HC12500, which are the pumps with the highest specific speed. It is important to note that the values of the relative and maximum errors are absolute and, as such, they do not offer insight into whether the method tends to overestimate or underestimate the extent of viscous degradation.

The model proposed by Ofuchi et al. (2020) also presents accurate predictions, mainly for the P37 and HC10000 models. This observation suggests an affinity of the model with more radial pumps, since its best performance occurred with pumps with lower specific velocities. For all ESP models, the MAPE ranged from 2.8% to 7.5%, the R^2 values were between 0.598 and 0.941, and the RMSE values ranging from 0.024 to 0.065. Gülich (2008) and Monte Verde (2016) are the least accurate models. The MAPE provided by Gülich (2008) ranges from 3.4% to 14.4%, with R^2 values spanning from −0.178 to 0.908, and RMSE values falling within the range of 0.031 to 0.096. On the other hand, the Monte Verde (2016) model presents MAPE values ranging from 2.8% to 11.6%, R^2 values between −0.298 and 0.920, and RMSE values varying between 0.025 and 0.086.

We can therefore state that all methods exhibit a satisfactory trend in predicting head at BEP, with the highest MAPE reaching 14.4% and RMSE and maximum relative error of 0.096 and 30.2%, respectively. Despite the favorable metrics, it is noteworthy that some methods yield negative R^2 values, which indicate specific limitations of the coefficient of determination. This emphasizes the significance of analyzing all available statistical metrics because each one provides distinct information and evaluating them individually may not be conclusive.

The comparison between experimental flow rate correction factor and that predicted by the methods for the BEP at 3000 rpm is shown in Fig. 3. Clearly, the points disperse and deviate from the ideal 45° line, revealing the limitations of the methods in predicting the flow

Table 1
Statistical evaluation of $C_{H,BEP}$ prediction by empirical models.

$C_{H,BEP}$		Step./TUALP (1949)	Gülich (2008)	ANSI-HI (2010)	KSB (1989)	M. Verde (2016)	Ofuchi et al. (2020)
P37	MAPE [%]	9.3	14.4	7.9	11.9	11.6	5.6
	$e_{r,m}$ [%]	13.9	21.0	12.9	17.5	30.2	11.0
	RMSE [-]	0.063	0.096	0.055	0.081	0.086	0.041
	R^2 [-]	0.492	−0.178	0.614	0.153	0.044	0.782
P47	MAPE [%]	3.2	3.4	4.5	2.7	6.1	7.5
	$e_{r,m}$ [%]	6.0	10.8	8.3	5.7	20.3	11.8
	RMSE [-]	0.029	0.031	0.042	0.025	0.055	0.065
	R^2 [-]	0.917	0.908	0.829	0.941	0.712	0.598
P62	MAPE [%]	6.1	9.4	2.3	4.1	8.1	4.6
	$e_{r,m}$ [%]	9.8	16.6	5.7	7.4	12.7	8.6
	RMSE [-]	0.050	0.072	0.021	0.035	0.070	0.039
	R^2 [-]	0.537	0.020	0.914	0.765	0.070	0.713
P100	MAPE [%]	7.8	9.0	3.1	5.2	8.7	3.9
	$e_{r,m}$ [%]	12.4	13.9	7.7	10.0	15.6	9.9
	RMSE [-]	0.063	0.071	0.029	0.045	0.076	0.035
	R^2 [-]	0.104	−0.130	0.807	0.551	−0.298	0.721
HC10000	MAPE [%]	6.8	7.4	5.0	8.6	5.1	2.8
	$e_{r,m}$ [%]	17.2	18.0	14.6	18.5	15.1	10.5
	RMSE [-]	0.051	0.056	0.039	0.063	0.042	0.024
	R^2 [-]	0.739	0.681	0.849	0.599	0.826	0.941
HC12500	MAPE [%]	3.0	3.7	1.9	2.7	2.8	4.5
	$e_{r,m}$ [%]	12.8	15.2	8.3	11.8	5.5	7.1
	RMSE [-]	0.028	0.035	0.018	0.026	0.025	0.039
	R^2 [-]	0.903	0.844	0.959	0.915	0.920	0.810

of pumps operating with viscous fluids. Almost one-third of the total points exhibit deviations exceeding 30%.

The points with the largest deviations are observed for the smallest C_Q values. This indicates the difficulty of models to predict flow rate in low Reynolds number scenarios. The analyzed methods encounter challenges for predicting the flow rate, with particular emphasis on the Gülich (2008) and ANSI-HI (2010) methods, where most points fall outside the ±50% range. The models proposed by Monte Verde (2016) and Ofuchi et al. (2020) are those that yield the most acceptable results. At 3000 rpm, the method proposed by Monte Verde (2016) achieves 100% of its predictions within the ±30% range, with 43% of them falling within ±10%. With slightly lower performance, the Ofuchi et al. (2020) method presents 98% of the points within the ±30% range and 38% within ±10%.

Additionally, there is a clear trend of the models proposed by Stepanoff (1949)/TUALP (2006), KSB (1989), Gülich (2008), ANSI-HI (2010), and Ofuchi et al. (2020) to underestimate the flow rate reduction. That is, the application of these methods would result in predicted flow rates greater than the real ones. The model proposed by Monte Verde (2016), on the other hand, tends to predict a flow rate lower than the measured one, overestimating the performance degradation.

Table 2 shows the statistical assessment of the flow rate predicted by empirical models. The model proposed by Ofuchi et al. (2020) yields the best MAPE, RMSE, and R^2 values for the P37 and HC10000 pumps, which are the ESPs with the lowest specific speeds. In general, the MAPE presented by this model varies between 12.9 and 18.7%, R^2 between 0.334 and 0.838, and the RMSE ranging from 0.064 to 0.090. However, it is important to note that this model exhibits significant maximum errors, which range from 23.7 to 46%. In terms of metrics, the model proposed by Monte Verde (2016) stands out as the one that offers the most accurate flow rate predictions for ESPs P47, P62, P100, and HC12500. This model provides a MAPE that ranges from 2.6% for pump P100 to 23% for pump P37. The R^2 varies between 0.091, for the worst-case scenario (HC10000) and 0.977 for the best case (P100). These observations suggest the model aligns better with ESPs with higher specific speeds. Furthermore, this model presents the lowest maximum error values compared to the others, ranging from 6% to 26.9%.

On the other hand, Table 2 confirms the poor accuracy of the Gülich (2008) and ANSI-HI (2010) standard models, rendering their application unfeasible. The MAPE of the Gülich's method ranges from 38.7% to 55.2%, with maximum errors between 76.9% and 121.9%. The R^2 varies between −5.058 and −1.027 and the RMSE ranges from 0.213 to 0.285. Similarly, the ANSI-HI (2010) demonstrates performance on par with Gülich (2008), exhibiting MAPE values between 35.5% and 46.4%, maximum errors ranging from 66.3% to 107%, and R^2 values that are inadequate, which range between −3.179 and −0.355. The RMSE varies from 0.186 to 0.234.

Fig. 4 shows the comparison between the efficiency correction factors measured at BEP and those predicted by the methods for different ESP models at 3000 rpm. The efficiency prediction is even more precarious, since this parameter propagates flow rate, head and shaft power deviations. These results present the comparison between the measured efficiency correction factor and that predicted by the methods, in the BEP, for all ESPs tested at 3000 rpm. At this rotational speed, more than 57% of the points are outside the ±30% range and 29% show deviations greater than ±50% from the measured value.

The methods of Gülich (2008), ANSI-HI (2010), and KSB (1989) yield predicted efficiencies significantly higher than the measured values, i.e. they underestimate the efficiency degradation. The model proposed by Monte Verde (2016), similar to its behavior in flow rate prediction, tends to overestimate performance degradation, resulting in lower efficiencies than the actual values. Furthermore, as observed for the flow correction coefficient, most points with high deviations are verified for the smallest values of experimental C_η, suggesting the difficulty of models in predicting efficiency for low Reynolds number conditions.

The statistical evaluation of the efficiency correction factor, shown in Table 3, indicates that none of the four methods evaluated provide suitable predictions. The preferable scenarios are the predictions from Monte Verde (2016), specifically for P62 and that of KSB (1989) for P100. However, in both cases, the MAPE is greater than 17%, the maximum error is greater than 39%, and the R^2 is less than 0.815. The Gülich (2008) model is the one that presents the worst efficiency prediction. The MAPE ranges from 50.8 to 131.2% and the maximum error is between 111.7 to 253.3%. These metrics clearly indicate that the application of this methodology is not feasible for predicting the efficiency of ESPs operating under viscous conditions.

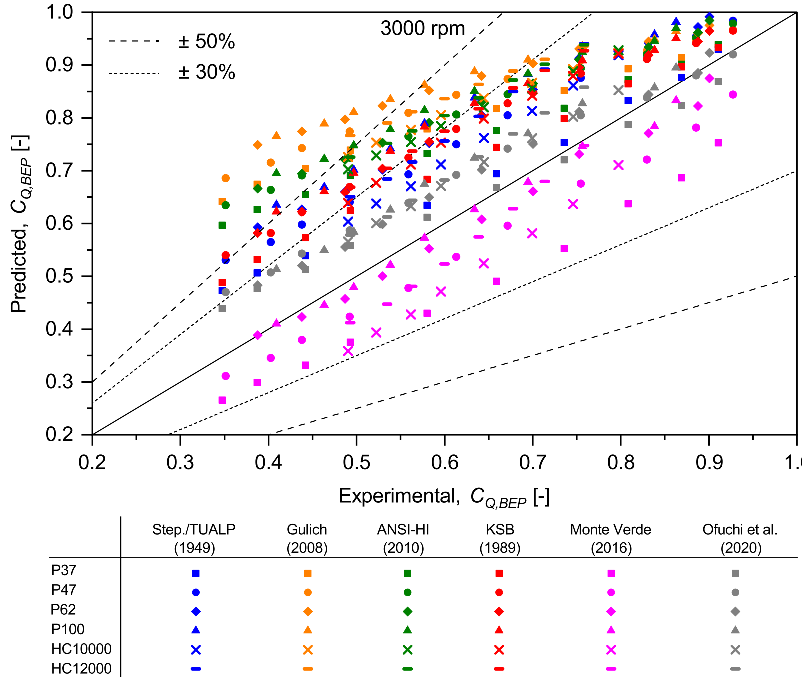

Fig. 3. Comparison between the measured and predicted flow rate correction factor at BEP for different ESP models at 3000 rpm.

Table 2
Statistical evaluation of $C_{Q,BEP}$ prediction by empirical models.

$C_{Q,BEP}$		Step./TUALP (1949)	Gülich (2008)	ANSI-HI (2010)	KSB (1989)	M. Verde (2016)	Ofuchi et al. (2020)
P37	MAPE [%]	18.3	47.5	38.9	24.9	23.0	12.9
	$e_{r,m}$ [%]	61.1	121.9	107.0	61.7	25.8	46.0
	RMSE [-]	0.088	0.227	0.186	0.119	0.131	0.064
	R^2 [-]	0.693	−1.027	−0.355	0.445	0.320	0.838
P47	MAPE [%]	30.6	55.2	46.4	34.6	12.7	18.7
	$e_{r,m}$ [%]	63.6	115.4	99.3	63.0	16.9	41.8
	RMSE [-]	0.148	0.266	0.223	0.169	0.069	0.090
	R^2 [-]	−0.241	−2.993	−1.813	−0.606	0.733	0.540
P62	MAPE [%]	33.5	54.5	42.4	32.6	4.4	13.7
	$e_{r,m}$ [%]	66.5	115.6	90.2	60.7	7.1	32.4
	RMSE [-]	0.175	0.283	0.220	0.170	0.028	0.071
	R^2 [-]	−0.987	−4.174	−2.126	−0.876	0.950	0.670
P100	MAPE [%]	37.7	53.4	43.9	35.7	2.6	16.3
	$e_{r,m}$ [%]	63.7	101.8	81.9	58.5	6.0	29.4
	RMSE [-]	0.203	0.285	0.234	0.192	0.018	0.088
	R^2 [-]	−2.074	−5.058	−3.090	−1.747	0.977	0.421
HC10000	MAPE [%]	22.0	38.7	35.5	27.6	20.5	14.2
	$e_{r,m}$ [%]	47.1	84.3	79.0	52.2	26.9	34.7
	RMSE [-]	0.122	0.213	0.195	0.153	0.117	0.078
	R^2 [-]	0.015	−1.992	−1.514	−0.549	0.091	0.596
HC12500	MAPE [%]	27.5	42	36.7	29.6	12.5	14.3
	$e_{r,m}$ [%]	43.2	76.9	66.3	44.5	18.8	23.7
	RMSE [-]	0.159	0.238	0.208	0.17	0.073	0.083
	R^2 [-]	−1.447	−4.461	−3.179	−1.804	0.486	0.334

Fig. 5 shows the influence of viscosity on the prediction errors for head, flow rate and efficiency, at BEP, for the ESP P47 and rotational speed of 3000 rpm. In general, the trends observed under these conditions are consistent for the other ESP models and rotational speeds. With the exception of the model proposed by Monte Verde (2016), the methods yield relatively consistent results in predicting pump head, with minimal error variation concerning increasing viscosity. However, flow rate and efficiency predictions are notably influenced by viscosity. All methods exhibit a substantial increase in prediction errors as viscosity increases. Among these models, Gülich (2008) is the most affected when it comes to flow rate and efficiency prediction. At 3000 rpm, the prediction efficiency error increases from 9.2% to 107.3% as viscosity increases from 24 mPa s (20 mm^2/s) to 1273 mPa s (1020 mm^2/s). For the same viscosity range, the prediction flow rate error increases from 4.3% to 95.2%.

When considering Brazilian fields, as a production scenario, where the oil viscosity can reach as high as 365 mPa s under reservoir conditions (Bulgarelli et al., 2023) the application of the original empirical models can result in a substantial over or underestimation of both flow rates and efficiency, with uncertainties around 50% and 80%, respectively. This situation may require the design of an over or undersized ESP system and separator tank on the platform, and cause an overload of the ESP motor, for example. Consequently, such a scenario could lead to elevated production costs, reduced available

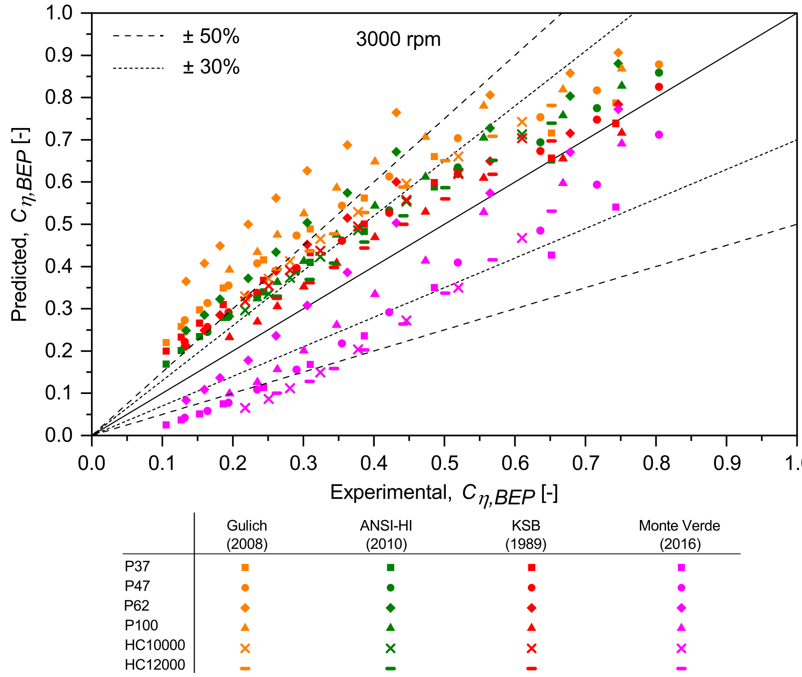

Fig. 4. Comparison between the measured and predicted efficiency correction factor at BEP for different ESPs models at 3000 rpm.

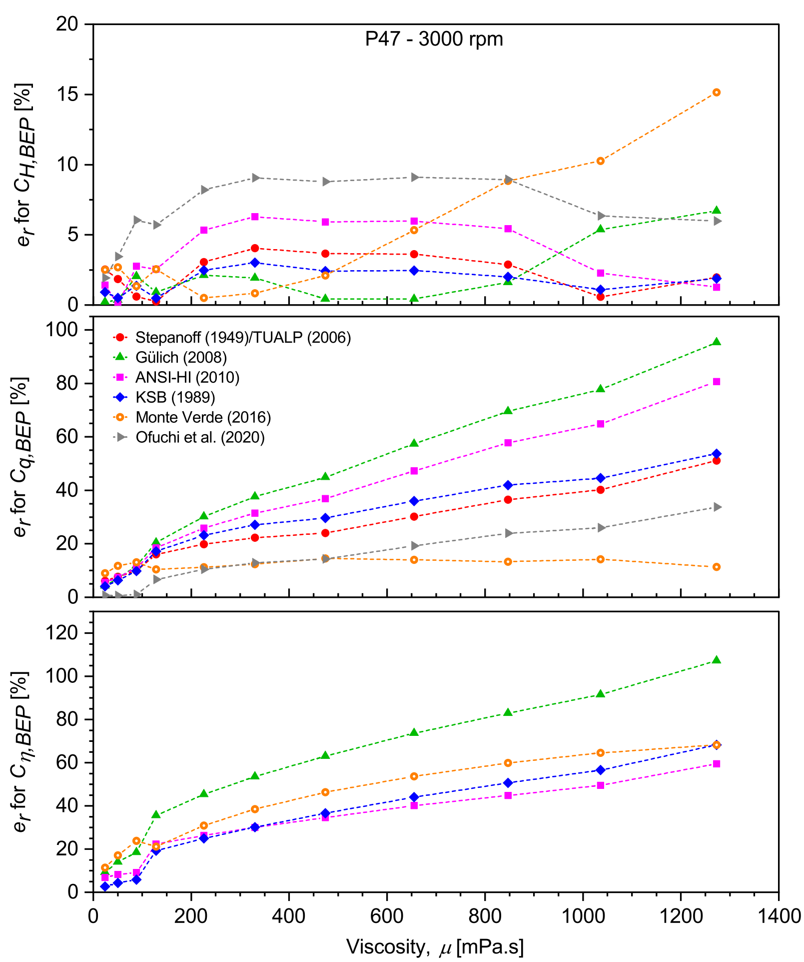

Fig. 5. Prediction errors of head, flow rate, and efficiency of ESP P47 operating at different viscosities and 3000 rpm.

Table 3
Statistical evaluation of $C_{\eta,BEP}$ prediction by empirical models.

$C_{\eta,BEP}$		Gülich (2008)	ANSI-HI (2010)	KSB (1989)	Monte Verde (2016)
P37	MAPE [%]	83.3	48.3	64.2	54.3
	$e_{r,m}$ [%]	184.3	115.4	161.5	76.1
	RMSE [-]	0.162	0.094	0.119	0.116
	R^2 [-]	−0.585	0.468	0.153	0.192
P47	MAPE [%]	74.1	42.0	45.2	47.8
	$e_{r,m}$ [%]	159.8	96.8	108.3	68.4
	RMSE [-]	0.174	0.099	0.102	0.119
	R^2 [-]	−0.736	0.433	0.397	0.190
P62	MAPE [%]	131.2	74.0	53.6	18.4
	$e_{r,m}$ [%]	253.3	132.4	91.5	39.7
	RMSE [-]	0.291	0.175	0.127	0.045
	R^2 [-]	−6.788	−1.823	−0.489	0.812
P100	MAPE [%]	74.6	39.0	17.4	28.1
	$e_{r,m}$ [%]	151.4	78.7	39.5	50.2
	RMSE [-]	0.225	0.123	0.056	0.084
	R^2 [-]	−2.349	−0.007	0.792	0.529
HC10000	MAPE [%]	57.1	43.5	49.9	50.7
	$e_{r,m}$ [%]	125.0	102.3	125.0	72.8
	RMSE [-]	0.151	0.114	0.126	0.143
	R^2 [-]	−0.194	0.316	0.166	−0.066
HC12500	MAPE [%]	50.8	30.5	26.6	43.7
	$e_{r,m}$ [%]	111.7	72.5	70.2	64.8
	RMSE [-]	0.160	0.097	0.082	0.144
	R^2 [-]	−0.319	0.509	0.656	−0.070

space on the platform, potential production shutdowns and uncertainty to estimate the CO_2 emissions.

4.2. Optimization and improvements of empirical models

The significant deviations between the experimental correction factors and those predicted by the methods, particularly in the prediction of flow rate and efficiency, emphasize the need for developing correlations based on specific databases for ESPs. The models' coefficients optimized for the ESP database are shown in Appendix. This section presents an analysis of the predictions provided by the modified models.

While it is a common practice to separate a dataset into test and training sets to avoid data bias and enhance predictive model reliability, the dataset used in this study, despite its significance, remains relatively small for this division. Nevertheless, we conducted test studies where 70.2% of the experimental data (127 points) represented the training sets, while the remaining 29.8% (54 points) comprised the test sets. Minimal differences were observed between the optimization results using this method compared to those using the entire database. As a result, we opted to work with optimizations derived from adjustments using the complete database so as to maintain a more comprehensive representation of the data points and model characterization.

Since the improvements of the methods involved simultaneous optimization of all constants to minimize prediction errors for the three correction factors, our analyses were based on global parameters. We compared the concatenated vector of correction factors calculated by the modified models with the concatenated vector of experimentally measured correction factors provided by the database. This analysis allows us to evaluate which method performs better in predicting the operation of all ESPs stage models in the dataset. It also helps us assess the effectiveness of each method in predicting the overall performance of the pump, rather than just one coefficient.

Given that not all models provide predictions for the three correction factors, the optimization results were evaluated in two separate sets. Table 4 presents the global statistical parameters of head and flow rate forecasts, for the original and optimized models. While Table 5 presents the global statistical parameters of head, flow rate, and efficiency predictions, also before and after optimization. For example, Table 4 presents a MAPE of 14.9% for the original Stepanoff (1949)/TUALP (2006) model, while the same model, after optimization, exhibits a MAPE of 5.0%. In other words, the average error in predicting the flow rate and head at BEP, considering all ESPs models, rotational speeds, and viscosities in the database changed from 14.9 to 5.0%.

All modified models exhibited significant improvements. After optimization, the Stepanoff (1949)/TUALP (2006), KSB (1989), Monte Verde (2016), and Ofuchi et al. (2020) methods demonstrated excellent performance in predicting head and flow rate, with MAPE ranging from 3.6% to 5.0%, maximum error between 13.1% and 23.5%, RMSE between 0.032 and 0.042, and R^2 ranging from 0.935 to 0.964. The Gülich (2008) and ANSI-HI (2010) models also presented considerable improvement in global head and flow rate prediction performance; however, they still had the highest deviations, with MAPE close to 13.5%, maximum error approaching 57.6%, RMSE of 0.094, and R^2 of 0.682.

By including efficiency prediction, the four models shown in Table 5 exhibit even more substantial improvements compared to their original performance. After optimization, the KSB (1989) and Monte Verde (2016) methods maintain the best performance in predicting head, flow rate, and efficiency, with MAPE now varying between 5.2% and 5.9%, the maximum error between 36.7% and 41.8%, RMSE between 0.033 and 0.036, and R^2 ranging from 0.977 to 0.980.

The greater ability of the methods to predict the global performance of ESPs under viscous flow is evident. Then, the behavior of the optimized methods in predicting each correction factor was analyzed individually.

Fig. 6 shows the comparison between the head correction factor measured at the BEP and those predicted by the optimized methods for all ESPs at 3000 rpm. After optimization, except for the Gülich (2008) and ANSI-HI (2010), all other models demonstrated improvements compared to Fig. 2, which presents the same analysis before optimization. At 3000 rpm, 96% of the predicted points fall within the error range of ±10%, and 75% exhibit deviations smaller than 5%.

Table 6 shows the comparison between the head predictions of the original models and the optimized models, considering all ESPs, viscosities, and rotational speeds in the dataset.

After optimization, the models proposed by Stepanoff (1949)/TUALP (2006), KSB (1989), Monte Verde (2016), and Ofuchi et al. (2020)

Table 4
Comparison of global statistical parameters for head and flow rate prediction for the original and optimized models for all ESPs and rotational speeds.

$C_{H,BEP}$, $C_{Q,BEP}$		Step./TUALP (1949)	Gülich (2008)	ANSI-HI (2010)	KSB (1989)	M. Verde (2016)	Ofuchi et al. (2020)
Original	MAPE [%]	14.9	23.6	18.9	15.6	9.3	8.4
	$e_{r,m}$ [%]	66.5	121.9	107.0	63.0	30.2	46.0
	RMSE [-]	0.106	0.167	0.138	0.111	0.075	0.058
	R^2 [-]	0.592	−0.007	0.311	0.558	0.797	0.877
Optimized	MAPE [%]	5.0	13.5	13.6	3.6	3.6	3.6
	$e_{r,m}$ [%]	23.5	57.8	57.4	13.1	16.3	14.0
	RMSE [-]	0.042	0.094	0.094	0.032	0.032	0.032
	R^2 [-]	0.935	0.682	0.682	0.964	0.964	0.963

Table 5
Comparison of global statistical parameters for head, flow rate and efficiency prediction for the original and optimized models, for all ESPs and rotational speeds.

$C_{H,BEP}$, $C_{Q,BEP}$, $C_{\eta,BEP}$		Gülich (2008)	ANSI-HI (2010)	KSB (1989)	Monte Verde (2016)
Original	MAPE [%]	37.7	25.6	22.1	18.1
	$e_{r,m}$ [%]	253.3	132.4	161.5	76.1
	RMSE [-]	0.174	0.131	0.106	0.092
	R^2 [-]	0,464	0,698	0,801	0,850
Optimized	MAPE [%]	12.5	11.5	5.2	5.9
	$e_{r,m}$ [%]	57.8	57.4	36.7	41.8
	RMSE [-]	0.081	0.080	0.033	0.036
	R^2 [-]	0.885	0.888	0.980	0.977

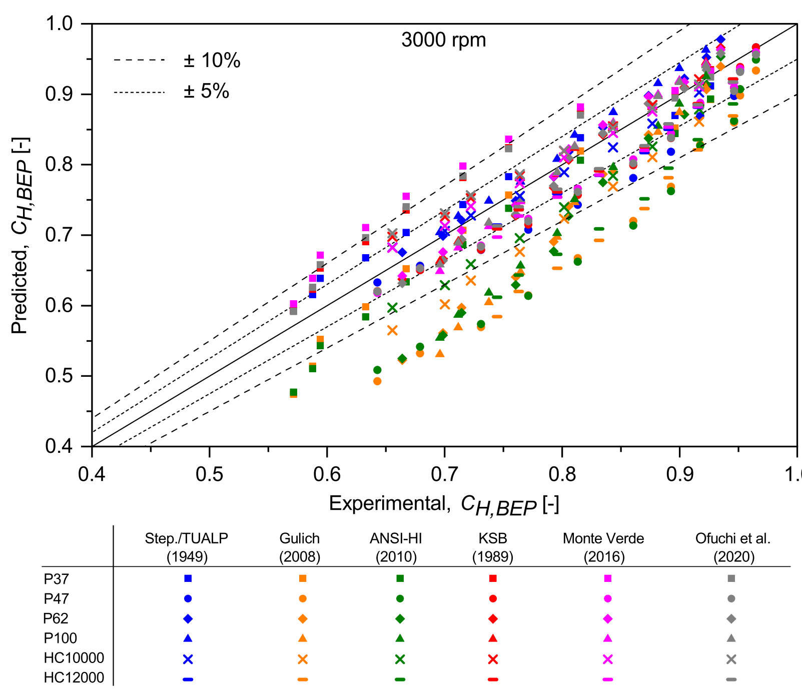

Fig. 6. Comparison between the measured and predicted head correction factor for optimized models, at BEP, for different ESPs and 3000 rpm.

Table 6
Comparison of statistical parameters for head prediction for the original and optimized models, for all ESPs and rotational speeds.

$C_{H,BEP}$		Step./TUALP (1949)	Gülich (2008)	ANSI-HI (2010)	KSB (1989)	M. Verde (2016)	Ofuchi et al. (2020)
Original	MAPE [%]	5.5	6.8	3.7	5.2	6.5	4.3
	$e_{r,m}$ [%]	17.2	21.0	14.6	18.5	30.2	11.8
	RMSE [-]	0.048	0.059	0.035	0.046	0.060	0.039
	R^2 [-]	0.823	0.732	0.907	0.832	0.721	0.879
Optimized	MAPE [%]	3.5	11.1	10.8	3.8	3.9	3.8
	$e_{r,m}$ [%]	13.4	25.2	23.6	13.1	16.3	14.0
	RMSE [-]	0.033	0.096	0.093	0.035	0.037	0.035
	R^2 [-]	0.914	0.276	0.328	0.905	0.894	0.903

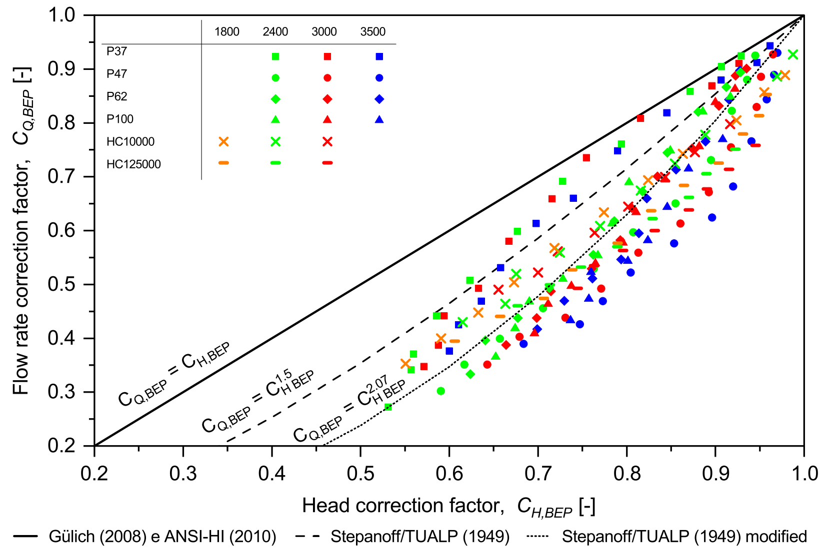

Fig. 7. Comparison of experimental flow rate and head correction factors at BEP.

demonstrated suitable results with statistically similar performance. They yield MAPE and RMSE values of approximately 3.8% and 0.035, maximum error and R^2 values around 14% and 0.904, respectively. We can therefore conclude that these models, after being adjusted, are suitable for predicting the head of ESPs in the database under viscous flow.

Furthermore, the optimized Gülich (2008) model and the ANSI-HI (2010) standard exhibit less accurate head predictions compared to the original models. Although there is an increase in deviations in the head prediction, as analyzed in Table 4 and Table 5, there is a significant improvement in their global performance, i.e. the prediction of the head, flow rate and efficiency. This is associated with the simplification introduced by both models, which assume that the flow rate correction factor is always equal to the head correction factor at the BEP point, denoted as $C_Q = C_{H,BEP}$.

Fig. 7 presents a comparison between the experimental flow rate and head correction factors at the BEP. The experimental data deviate from the hypothesis proposed by the Gülich (2008) and the ANSI-HI (2010) standards mentioned earlier, i.e. $C_Q = C_{H,BEP}$. When attempting to optimize all correction factors simultaneously, the algorithm yields optimal parameters. These parameters may lead to a degradation in head prediction performance, but this is compensated for by substantial improvements in flow rate and efficiency predictions of these models, resulting in the lowest possible global RMSE.

These results also demonstrate that the hypothesis from Stepanoff (1949), which proposes that the degradation of pump performance at the BEP occurs while maintaining a constant specific speed, resulting in $C_{Q,BEP} = C^{1.5}_{H,BEP}$, is not applicable for accurately predicting the ESP performance operating with viscous fluids. After optimizing the Costa et al. (2013)/TUALP (2006) method, the same approach adopted by Ofuchi et al. (2020), the significant dispersion of points around the dotted line indicates that this formulation is generally unsuitable, particularly for ESPs with lower specific speeds. A direct correlation between $C_{Q,BEP}$ and $C_{H,BEP}$ proves inadequate in capturing the experimental data of all ESPs, as each exhibits distinct and well-defined trends. This suggests the influence of specific speed on the head and flow rate correction factors.

Regarding flow rate prediction, Fig. 8 shows the comparison between the flow rate correction factors measured at BEP and those predicted by the optimized methods for all ESPs and rotational speed of 3000 rpm. Table 7 presents comparisons between the statistical parameters of the original and optimized models, including all pumps, viscosities, and rotational speeds.

Comparing Fig. 8 with Fig. 3, which represents the original performance of the models, it is evident that all models show significant improvements, particularly the methods of Stepanoff (1949)/TUALP (2006), KSB (1989), Monte Verde (2016), and Ofuchi et al. (2020). Among these methods, 100% of flow rate predictions after optimization fall within the range of ±30% and 93% have deviations smaller than 10%. Additionally, the high deviations previously observed for the lowest values of experimental $C_{Q,BEP}$ are no longer present after modifying the coefficients. This suggests that, for these models, optimization may have corrected the tendency for the error in flow prediction to increase with the reduction in the Reynolds number.

The methods of KSB (1989), Monte Verde (2016), and Ofuchi et al. (2020) provide satisfactory results for flow rate prediction after the coefficients were readjusted using the ESP database. With similar performance, they demonstrate a MAPE of approximately 3.3%, a maximum error of 11.4%, an RMSE of 0.027, and R^2 of approximately 0.974. After optimization, any of these models can be considered suitable for predicting the flow rate at the BEP of ESPs operating with viscous fluids within the database operational range. Despite optimization, the performance of the Gülich (2008) and ANSI-HI (2010) models continues to be the least satisfactory among the analyzed methods for predicting viscous flow rate. The significant deviations observed can be attributed to the simplifications made by the authors, as discussed earlier. Optimization aims to minimize the global RMSE, but it is challenging to predict both correction factors (head and flow rate) accurately because the experimental data do not support the assumption of $C_{Q,BEP} = C_{H,BEP}$.

For the prediction of ESP efficiency in viscous operation, Fig. 9 shows the comparison between the efficiency correction factors measured at the BEP and those predicted by the modified methods for all ESPs operating at 3000 rpm. Additionally, Table 8 provides comparisons of the statistical parameters of the original models and after optimization, considering all ESPs, viscosities, and rotational speeds.

The models proposed by Gülich (2008) and Monte Verde (2016) exhibited similar performance in predicting $C_{\eta,BEP}$, with their data points in Fig. 9 overlapping. The enhancements in model predictions after adjusting the empirical coefficients are substantial. At 3000 rpm, the original methods yielded results where only roughly 43% of the predicted efficiency points were within the ±30% error range. Following optimization, this metric rose to 99%, with 68% of the points with deviations under 10%. Table 8 confirms the substantial improvement in predicting the efficiency of ESPs operating with viscous fluids. The ANSI-HI (2010) and KSB (1989) standard models deliver the best

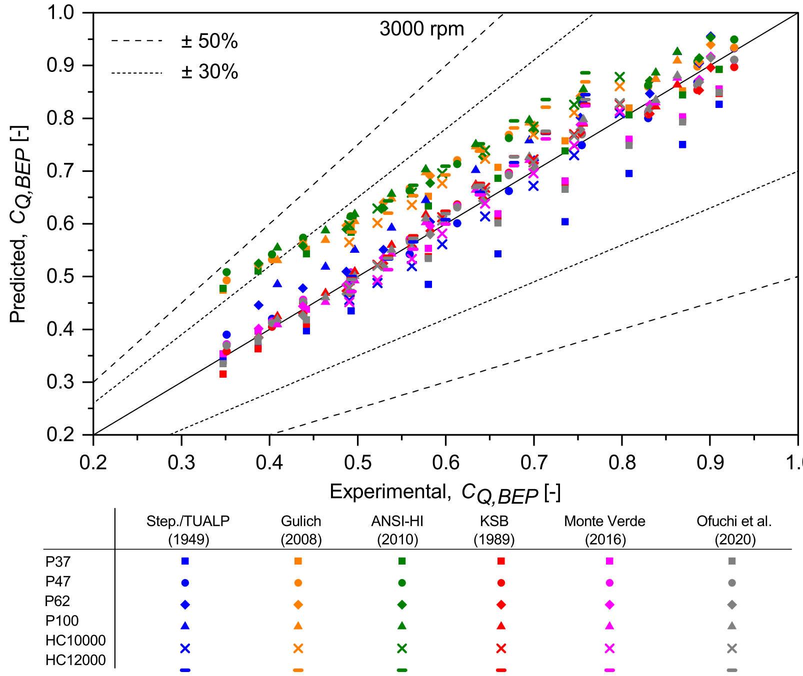

Fig. 8. Comparison between the measured and predicted flow rate correction factor for optimized models, at BEP, for different ESPs and 3000 rpm.

Table 7
Comparison of statistical parameters for flow rate prediction for the original and optimized models, for all ESPs and rotational speeds.

$C_{Q,BEP}$		Step./TUALP (1949)	Gülich (2008)	ANSI-HI (2010)	KSB (1989)	M. Verde (2016)	Ofuchi et al. (2020)
Original	MAPE [%]	24.4	40.4	34.2	26.1	12.1	12.5
	$e_{r,m}$ [%]	66.5	121,9	107.0	63.0	26.9	46.0
	RMSE [-]	0.143	0.229	0.193	0.150	0.088	0.073
	R^2 [-]	0.297	−0.811	−0.279	0.227	0.734	0.818
Optimized	MAPE [%]	6.4	16.0	16.5	3.4	3.2	3.3
	$e_{r,m}$ [%]	23.5	57.8	57.4	10.4	13.2	10.7
	RMSE [-]	0.050	0.092	0.095	0.028	0.025	0.028
	R^2 [-]	0.914	0.711	0.689	0.972	0.978	0.972

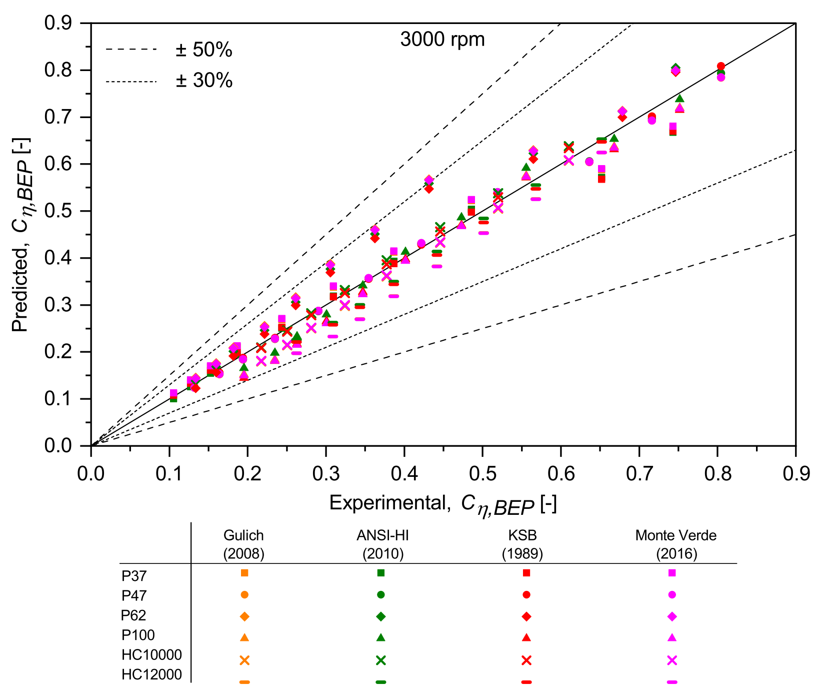

Fig. 9. Comparison between the measured and predicted efficiency correction factor for optimized models, at BEP, for different ESPs and 3000 rpm.

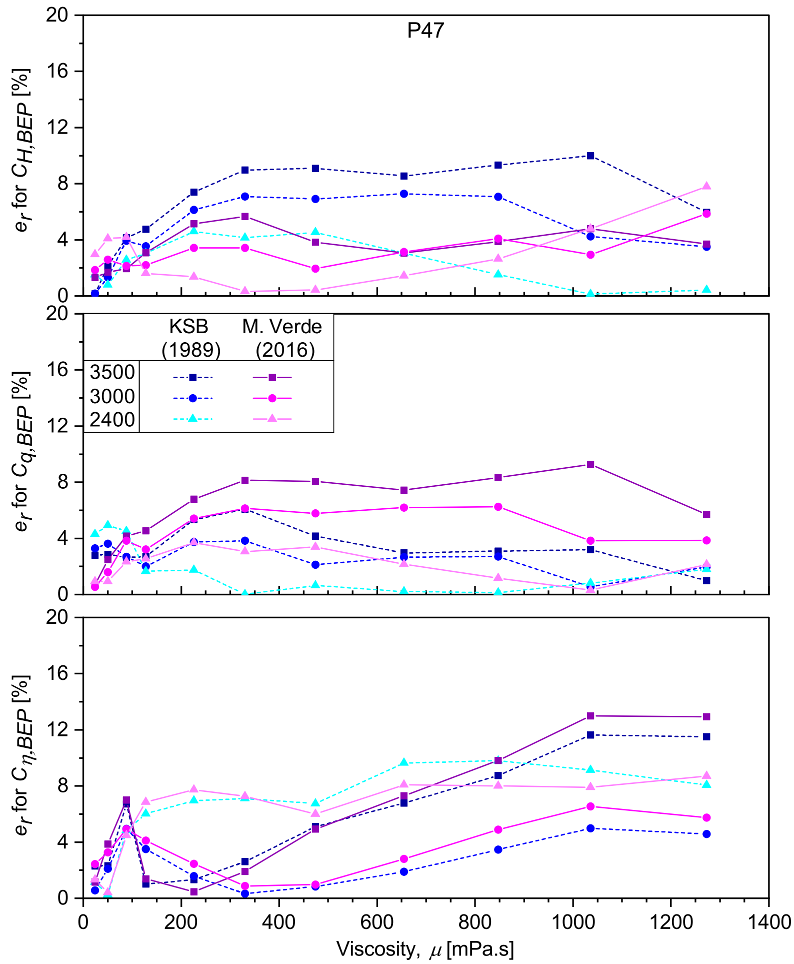

Fig. 10. Prediction errors of head, flow rate, and efficiency of ESP P47, using optimized methods of KSB and Monte Verde, operating at different viscosities and rotational speeds.

Table 8
Comparison of statistical parameters for efficiency prediction for the original and optimized models, for all ESPs and rotational speeds.

$C_{\eta,BEP}$		Gülich (2008)	ANSI-HI (2010)	KSB (1989)	Monte Verde (2016)
Original	MAPE [%]	65.8	38.8	35.0	35.7
	$e_{r,m}$ [%]	253.3	132.4	161.5	76.1
	RMSE [-]	0.187	0.114	0.096	0.119
	R^2 [-]	0.186	0.699	0.788	0.672
Optimized	MAPE [%]	10.4	7.1	8.5	10.5
	$e_{r,m}$ [%]	42.4	35.8	36.7	41.8
	RMSE [-]	0.043	0.036	0.036	0.043
	R^2 [-]	0.957	0.970	0.970	0.957

results with a MAPE of approximately 7.8%, a maximum error of around 36%, an RMSE of 0.036, and R^2 of 0.970.

To investigate the effect of the Reynolds number on the performance of the optimized models, Fig. 10 shows the relative errors obtained by the KSB (1989) and Monte Verde (2016) models for the ESP P47 predictions, operating at different rotational speeds and viscosities. These models were considered for this analysis because they presented the lowest global RMSE in predicting head, flow rate, and efficiency. For head prediction, the errors obtained by the optimized models remain consistent with the variations in viscosity, except for the Monte Verde (2016) model, which exhibits a slight increase for viscosities greater than 847 mPa s. Additionally, the KSB (1989) model shows a tendency to reduce the error as the rotation speed decreases.

When predicting flow rate, both models show consistent errors with minimal influence from viscosity. The results of the KSB (1989) and Monte Verde (2016) models show a tendency for error reduction with decreasing rotational speed. However, when predicting efficiency, the behavior of errors provided by the models does not follow a well-defined trend. At speeds of 3000 and 3500 rpm, both models exhibit a moderate but continuous increase in errors for viscosities greater than 330 mPa s.

While there is still some correlation between the Reynolds number and the errors observed in the optimized models, a comparison with the original predictions suggests that the optimization has effectively mitigated these effects. Returning to the Brazilian fields scenario, it is notable that the uncertainty in ESP flow rate and efficiency, as predicted by the optimized models, has been significantly reduced by approximately 80% and 87%, respectively, when compared to the original models. This has significant implications for optimizing production, leading to cost reductions, more effective energy consumption planning, and enhanced accuracy in estimating CO_2 emissions.

5. Conclusions

This work provides a comprehensive assessment of six empirical models for predicting the performance of ESPs under viscous flow. To accomplish this, we used a vast database provided by Monte Verde et al. (2023) as our reference. Due to the considerable errors observed in these predictions, the methods were improved. The empirical constants of these methods were optimized considering the specific database of ESPs. The following conclusions were obtained:

- The original models have limitations due to their restricted databases, primarily based on data from conventional centrifugal pumps. This limitation significantly affected the models' performance in predicting the behavior of the tested ESPs, providing unfeasible results. The significant deviations between the experimental correction factors and those predicted by the methods, particularly in the prediction of flow rate and efficiency, emphasize the need for developing correlations based on specific databases for ESPs. Furthermore, some models provide predictions only for the BEP and may only predict flow rate and head, without including efficiency.
- The original model predictions for the viscous performance of ESPs can lead to significant errors in the sizing of the production system. For instance, the Gülich model exhibits a maximum error of 253% in predicting the efficiency of ESP P62. This means that the system could be undersized, with insufficient power to deliver the designed flow rate, or potentially oversized. While oversizing may be less problematic than undersizing, it still has significant consequences, such as increased costs related to cables, casing, penetrators, electric generators, platform area, and other components, which can substantially increase the cost of the artificial lift system. Based on the analyses conducted in this study, the use of these models in their original form does not appear suitable for accurately predicting the viscous performance of ESPs.
- The accuracy of the models improved significantly after modifying the methods. Reductions in errors were observed in all correction factors, and particularly in the prediction of global performance. In practical applications and for sizing of artificial lifting systems that utilize ESPs, the modified models are more recommended compared to the original ones.
- In general, the modifications were effective in mitigating the effects of increased deviations with the reduction in Reynolds number observed when applying the original models to predict flow rate and efficiency.
- Analyzing the head and flow rate predictions, it became evident that direct relationships between $C_{Q,BEP}$ and $C_{H,BEP}$ are insufficient to represent the global performance of the ESPs. We hypothesize that the specific speed has an influence on the correlation between these variables.
- Despite the substantial improvement in the accuracy of the modified empirical models, the opportunity remains to develop dedicated models tailored for predicting ESP performance. We recommend that these models consider the specific speed of ESPs and explore alternative functional relationships to enhance the accuracy of the prediction.

Nomenclature

$a, b, c, \dots, i$ = empirical constants, dimensionless
B = dimensionless parameter of KSB and ANSI-HI models, dimensionless
B_{HI} = dimensionless parameter of KSB model, dimensionless
C_H = head correction factor, dimensionless
C_Q = flow rate correction factor, dimensionless
C_η = efficiency correction factor, dimensionless
e_r = absolute relative error, dimensionless, %
g = gravity acceleration, Lt^{-2}, m/s^2
H = head, L, m
$MAPE$ = mean absolute percentage error, dimensionless, %
Q = volumetric flow rate, L^3t^{-1}, m^3/h
r_2 = impeller outer diameter, L, m
R^2 = coefficient of determination, dimensionless
$Re_{evdocia}$ = modified Reynolds number, dimensionless
$Re_{Gülich}$ = modified Reynolds number, dimensionless
Re_{Ofuchi} = modified Reynolds number, dimensionless
Re_ω = rotational Reynolds number, dimensionless
$RMSE$ = root mean squared error, the same unit of the analyzed parameter
x, y, z = dimensionless parameter, dimensionless
β = dimensionless parameter of KSB, dimensionless
η = efficiency, dimensionless [%]
Δn_Q = dimensionless parameter of KSB, dimensionless
ω = rotational speed, nt^{-1}, rpm
ω_S = specific speed, dimensionless
ν = kinematic viscosity, Lt^{-2}, mm^2/s
ξ = correction factor of KSB model, dimensionless

CRediT authorship contribution statement

William Monte Verde: Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Formal analysis. **Ellen Kindermann:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Natan Augusto Vieira Bulgarelli:** Writing – review & editing, Conceptualization. **Luiz Fernando Pastre:** Writing – review & editing. **Bernardo Foresti:** Writing – review & editing, Supervision. **Antonio Carlos Bannwart:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: William Monte Verde reports financial support was provided by Petrobras. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

See Table 9.

Table 9
Original and optimized empirical constants of the analyzed models.

Model	Coefficients	Original	Optimized
Stepanoff/TUALP (1949)	a	1.5	2.06
	b	0.033823	0.05484
	c	0.36769	0.30966
KSB (1989)	a	15	10.41
	b	0.013	0.039
	c	0.165	0.113
	b	4	5.323
	e	0.25	0.390
	f	0.75	0.643
	g	0.083	0.153
	h	0.59	0.547
	i	0.005	0.004
Gülich (2008)	a	1.5	0.507
	b	6.7	12.09
	c	0.735	0.709
	b	19	26.24
	e	0.705	0.663
ANSI-HI (2010)	a	0.5	0.429
	b	0.0625	−0.084
	c	0.375	0.243
	b	0.25	0.162
	e	2.71	2.652
	f	0.165	0.144
	g	3.15	3.829
	h	0.0547	0.026
	i	0.69	0.904
Monte Verde (2016)	a	1.5	0.462
	b	145.965	10.246
	c	1.139	0.741
	b	9.257	17.581
	e	0.610	0.714
	f	41.651	26.347
	g	0.688	0.663
Ofuchi et al. (2020)	a	1.5	2.084
	b	4.462	5.306
	c	0.695	0.735

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