Advanced Electric Submersible Pump Design Tool for Geothermal Applications

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Abstract

Electrical Submersible Pumps (ESPs) present higher efficiency, larger production rate, and can be operated in deeper wells than the other geothermal artificial lifting systems. Enhanced Geothermal Systems (EGS) applications recommend lifting 300°C geothermal water at 80kg/s flow rate in a maximum 10-5/8” diameter wellbore to improve the cost-effectiveness. In this paper, an advanced ESP design tool comprising a 1D theoretical model and a 3D CFD analysis has been developed to design ESPs for geothermal applications. Design of Experiments was also performed to optimize the geometry and performance. The designed mixed-flow type centrifugal impeller and diffuser exhibit high efficiency and head rise under simulated EGS conditions. The design tool has been validated by comparing the prediction to experimental data of an existing ESP product.

Key Words: Electrical Submersible Pumps, Enhanced Geothermal Systems, Design Tool, Mixed-Flow Centrifugal Pump, Impeller, Diffuser, CFD

Introduction

Enhanced Geothermal Systems (EGS) energy production entails hydraulic stimulation to enable or enhance energy production from hot dry rock. In most applications, hydraulic drive from ground level circulation pumps is limited; otherwise the thermal reservoir may be damaged with undesirable fractures and short circuits. Therefore artificial lift techniques must be employed to return the high temperature water back to the surface for energy recovery, particularly in sites with deeper wells. Lifting is also needed to optimize energy production and minimize cost of energy. The U.S. Department of Energy is calling for a lifting system capable to
effectively boost 80kg/s of working fluid (water, with a gas fraction of 2% or less) by 300bar in a well that is nominally 10-5/8” in diameter. The operating temperature is up to 300°C. Compared to the traditional lifting mechanisms, such as Line Shaft Pump, Gas Lift, Progressing Cavity Pump, and Jet Pump, Electrical Submersible Pumps (ESPs) have better performance in terms of effectively handling larger production rate in deeper wells. ESPs incorporate a submerged electric motor unit driving a multistage centrifugal pump to produce flow back to the surface. The design aims to lift large volumes of high temperature water against a pressure difference within the production well in which the system is installed.

The multistage radial- or mixed-flow centrifugal pump is a key component to the ESP system in which flow and pressure are generated dynamically. Generally, lift or head developed by a single stage centrifugal pump is relatively low, due to the limited well casing diameter [1]. Thus, a multistage pump must consist of many stages stacked together in series to provide the desired lifting capability. Each stage consists of two basic components: a rotating set of impellers and a stationary diffuser, shown as Figure 1. The geothermal fluid (water) from the previous stage enters the impeller in an axial direction at a relatively low velocity and attains a higher velocity through the impeller due to the centrifugal force. The fluid then leaves the impeller with high kinetic energy that is converted into potential energy at the discharge of the diffuser, at higher pressure level than it was at the inlet of the impeller. Since the diffuser redirects the flow into the next stage, the process repeats and the rotary action is finally converted to an increase of the fluid pressure. However, the theoretical design of such rotating machinery remains very empirical because it is hard to predict three-dimensional unsteady flow in varying locations, and one must rely on numerous experimental and statistical rules [2-4].

In this investigation, an advanced ESP design tool was developed by combining a one-dimensional theoretical model with a three-dimensional Computational Fluid Dynamics (CFD) analysis. The numerical simulation of both single phase flow and water/air mixture multiphase flow are presented. The results of the simulation include streamlines, velocity and pressure distributions and Gas Volume Fraction (GVF) within the ESP flow channels. The designed mixed-flow multistage centrifugal pump is seen to be able to produce 80kg/s geothermal fluid (at 300°C) with high efficiency and meet Department of Energy’s design criteria. In order to validate the design tool and methodology, the same design practice was carried out for an existing ESP product. The performance curves such as efficiency, head and power consumption agree with the test data very well. It is shown that the advanced design tool presented in this study can help understand and predict 3D flow behavior in an ESP with sufficient accuracy. It also helps to significantly shorten the development cycle of ESP for geothermal applications.
Design Tool Description

Figure 2 describes the pump design tool and the design procedure. First, based on the desired performance (flow rate and head etc.) and operating conditions, a one-dimensional theoretical model is utilized to identify the right type of impeller, and calculate the basic dimensions of the blade and the flow passage. Second, a three-dimensional model is built with a commercial software package, ANSYS BladeModeler, according to the design parameters obtained from the 1D model. Third, a mesh of the fluid domain is performed in TurboGrid, and followed by a CFD analysis in CFX. Fourth, Design of Experiments (DOE) is performed to further improve the performance of the stage. There are certain parameters that play significant roles in determining a pump’s performance, such as blade count, splitter count, diameter, wrap angle, blade angle, vane angle, inlet and outlet width, and so on. The main purpose of DOE is to perturb various design parameters of the impeller/diffuser configuration and explore their effects on the boosting under the simulated environment so as to optimize the design.
The 1D model is basically a set of formulations that calculate the design parameters. The model has been calibrated by numerous experiments [5]. Given the rotational speed \( N \) (rpm), flow rate \( Q \) (gpm) and head \( \Delta H \) (ft), the specific speed of the pump \( N_s \) can be identified as

\[
N_s = \frac{N \sqrt{Q}}{(\Delta H)^{3/4}}
\]  

(1)

The pump type can be selected according to Figure 3 [5]. The specific speed of an ESP is usually between 1000 and 5000, thus a Radial Centrifugal Pump, Francis Centrifugal Pump and Mixed-flow Centrifugal Pump are generally applied to achieve better efficiency.
A maximum 10-5/8” wellbore is required by the U.S. Department of Energy for Enhanced Geothermal System (EGS) applications to improve the drilling cost-effectiveness. Therefore, the maximum overall outer diameter (OD) of the geothermal downhole ESP is approximately 9.4” according to API Standard 5CT. For the 300°C production water of Enhanced Geothermal applications, the Specific Gravity, SG = 0.72. Hence 80kg/s mass flow rate is equivalent to about a 1780gpm volumetric flow rate. For the operating speed and required head per stage for this application, a mixed-flow type centrifugal pump was selected.

As previously mentioned, a rotating impeller and a stationary diffuser constitute a single stage of the multistage centrifugal pump. The function of the impeller is to accelerate the produced water from a relatively low velocity to a higher velocity by the high-speed rotation. The kinetic energy of the fluid is then converted into potential energy at the discharge of the diffuser. Therefore, as a single stage, the impeller and diffuser work together to generate sufficient boost to overcome the resistance.

The conceptual design of the impeller/diffuser and stages are shown as Figures 4 and 5, respectively. The blade-to-blade views are defined in BladeModeler. The meridional view of a single stage (impeller/diffuser assembly) is displayed as Figure 6. The blue/red sections represent the geometry of the blades in the meridional face.
Figure 4 – Conceptual design – impeller/diffuser
With the aid of CFD, the complex internal flows in the impellers and diffusers can be well predicted, thus facilitating the design of pumps. This investigation presents a numerical simulation of the single phase three-dimensional flow in the impeller of a single stage centrifugal pump using CFD techniques and a commercial software, ANSYS CFX5 Release 13. The calculation predicts the performance curves of the impeller/diffuser stage.
Figure 7 shows the 3D impeller/diffuser geometry and the meshed fluid domain. Due to the periodicity of the blades, it is only necessary to study the fluid domain around one blade and set the periodic boundary conditions as indicated in the figure. Other boundary conditions and inputs include:

1. Inlet: total pressure applied in the rotation axis direction = 90 bar
2. Outlet: mass flow rate = 80 kg/s
3. Wall: general boundary condition by default (roughness: 250μm)
4. Fluid: Water at 300°C
5. Rotational impeller
6. Stationary diffuser

For single phase flow, the pump’s performance is not sensitive to the inlet total pressure. However, a pressure drop takes place at the pump intake during operation, thus the pump’s inlet has to be located at a certain depth under water where the intake pressure is still above the saturated pressure of 300°C geothermal water in order to avoid cavitation. The CFD simulation is carried out based on the standard k-ε turbulence model and shows good convergence after several hundred time-steps.

Results and Discussion

Figure 8 plots the velocity distribution at 50% span. It is found that the impeller/diffuser configuration is able to convert the mechanical energy of the rotation into the kinetic energy of the fluid very well at the given geothermal environment. A small amount of flow separation occurs at the trail edge of the diffuser due to the curved blade shape which is trying to guide the flow back to the axial direction. As a result, efficiency is compromised slightly at the first
stage, but it is insured that the flow direction is repeatable stage by stage so that every stage can have the same performance.

**Figure 8 – Velocity distribution at 50% span**

**Figure 9 - Contour of area averaged static pressure on meridional surface**
Figure 9 shows the predicted contour of area-averaged static pressure on the meridional surface. It is observed that the static pressure increases by approximately 2.5 bar at the discharge of the stage, which results in a static head rise of 32 m. The blades and the vane shape are seen to build up the pressure very well. In order to better evaluate the characteristic of the impeller/diffuser stage, the performance curves have to be plotted to describe the relation between flow rate and head.

As previously noted, Design of Experiments (DOE) is performed to establish optimized configurations that can run at higher efficiency and generate higher head for a given set of constant boundary conditions. BladeModeler and TurboGrid tool kit are utilized to generate and mesh different geometries to assess the performance change. The definitions of the parameters and some examples are presented as Figures 10 and 11.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
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<tr>
<td>B</td>
<td>Blade Count</td>
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<tr>
<td>S</td>
<td>Splitter Count</td>
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<tr>
<td>D</td>
<td>Impeller Dia.</td>
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<tr>
<td>θ</td>
<td>Wrap Angle</td>
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<td>Δβ</td>
<td>Blade Angle</td>
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<td>t</td>
<td>Blade Thickness</td>
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<td>a</td>
<td>Inlet Width</td>
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<td>b</td>
<td>Outlet Width</td>
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<tr>
<td>φ</td>
<td>Vane Angle</td>
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<tr>
<td>C₁ ~ C₄</td>
<td>Blade Start and end Coordinates</td>
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Figure 10 – Impeller/diffuser design parameters
In this investigation, some of the critical parameters that have been studied for the performance optimization, such as the impeller’s warp angle, blade count, inlet width, and diffuser wrap angle etc. After a few modifications, the stage’s performance curve is shown as Figures 12 and 13. The best efficiency of the stage occurs between 70 kg/s to 80 kg/s mass flow rate. For 80 kg/s, the efficiency is approximately 78%. A theoretical best efficiency of the stage is around 83% and the abovementioned flow conditions, but this efficiency requires the pump diameter to be greater than 10". For the limited geothermal wellbore diameter, 78% is the upper bound of impeller efficiency and can be considered a successful design. Furthermore, reducing wall surface roughness helps to increase efficiency. The wall roughness used in the simulation was from typical cast parts. The study shows that if a better finishing or coating can be applied to the blades, hub and shroud, efficiency could be further increased by 1-2%.
Figure 12 - Stage efficiency curve

Figure 13 - Stage head rise and power curves
The blade load of the impeller and diffuser at their 50% span is shown as Figure 14. It is seen that the pressure drop at the inlet of the stage is above 87.5bar, which is higher than the saturated pressure of the 300°C water (86bar). In addition, the load distribution along the blade is observed to be smooth. The pressure difference across the blade is within 1bar, which results in relatively low loading from the structural point of view.

Gas handling capability was also investigated for the stage. The proposed lifting system design aims to pump the process water with less than 2% gas volume fraction (GVF) with no significant pressure drop. It is observed from the multiphase CFD study, shown as Figure 15, that no significant air bubbles attach to the blades, hub and shroud under 2% overall GVF. The static pressure drops only 1.8% compared to the pure liquid case. Therefore, the pump design can handle 2% GVF without adding any additional components. For the gassy wells where more than 2% gas is contained in the water, a gas separator can always be placed in front of the intake of the pump.
In order to validate the entire design process of the impeller and diffuser, the same design and analysis procedure has been utilized to an existing ESP design to compare the prediction and the experimental data. Figures 16 and 17 show the comparison of the efficiency and the head rise. It is observed that the prediction agrees with the experimental data very well. Both the error of the predicted efficiency and predicted head are within 2% compared to the actual values. Therefore, the single stage impeller/diffuser design procedure developed in this program has been demonstrated to be effective and accurate, at least for the operating range over which experimental data exists.

A comparison between the designed geothermal pump and an existing Artificial Lift ESP pump is exhibited as Figure 18. Dimensionless coefficients, such as head coefficient, power coefficient and capacity coefficient, are compared. It is seen that the geothermal pump maintains high efficiency at a much wider span of capacity (flow rate) range. The best efficiency is also 5% higher than the existing ESP pump though operated at a lower rotating speed.
Difference between prediction and experiment is approximately 2%

Figure 16 – Prediction vs. experiment - efficiency

Error of head prediction is within 2%

Figure 17 – Prediction vs. experiment – head rise
Conclusions

In this investigation, an advanced Electrical Submersible Pump (ESP) design tool for Enhanced Geothermal Systems (EGS) applications has been developed. The tool combines theoretical model of centrifugal pump design, commercial CFD packages including ANSYS BladeModeler, TurboGrid and CFX, and Design of Experiments for optimization.

The designed geothermal ESP impeller and diffuser achieve excellent performance under the desired high temperature, high production rate EGS conditions. The pump can effectively build up sufficient pressure along the blades, and realize excellent flow repeatability stage by stage. In addition, the design demonstrates good gas-handling capability and high efficiency for a wide range of production rate. The design tool has been validated by comparing to an existing ESP product. The prediction shows good match with the experimental data.

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