A REVIEW OF HEAT-RELATED ESP STUDIES

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INTRODUCTION

Pumping technologies are the most used artificial lift method, with sucker rod pumps and electrical submersible pumps (ESP) being the two most common ones. ESPs have the most accumulated volume of produced liquid amounts (Zhu and Zhang, 2018). They are known for their mid to high liquid production rates, their reliability with a mean time between failures of around two years, and their flexibility to be adjusted to well conditions, especially when combined with a variable speed drive (VSD).

The downhole assembly of an ESP is typically composed of a motor, a seal or protector section, a gas separator, and a multistage centrifugal pump. The motor is powered by an electrical cable connected to surface equipment, including switchboards, junction box, transformers, and occasionally a variable speed drive (VSD). The surface equipment controls the ESP and ensures safe operations by disconnecting it from electricity in harmful scenarios. The motor is responsible for converting the cable's electrical signal to a shaft rotation, powering the pump. At each stage, the pump impeller converts shaft rotation into fluid kinetic energy, which is recovered in the form of fluid pressure at the pump casing.

The first step in designing an artificial lift system is to assure production by matching desired flow rates, well IPR and OPR curves, decline rates, and the multistage pump produced head throughout well life. Finding this match can be very challenging, and it is usually an iterative process. Once the artificial lift problem is solved, and a multistage pump is selected, other components of the ESP system can be designed. For instance, the required shaft torque and rotational speed can be estimated based on the required flow rate and pump characteristics. This information is used to find and select a suitable electric motor.

Electrical Submersible Pumps (ESPs) have their motors submerged in the producing fluids. One of the main concerns is the ability of the fluids to provide the required cooling to the motor. The general recommendation in the industry has been to have a minimum fluid velocity of 1 ft/s around the motor and local fluid temperatures lower than 250 °F for standard motors (Powers, 1994). The benefit of this rule of thumb is that it does not interfere with previous steps in the design process. If velocities around the motor are too low, a shroud can be introduced to accelerate the fluids above 1 ft/s. The downside is that the assumptions used for simplifying the problem are not clear, and hence there is a question of whether it is applicable. It does not seem universally applicable, especially for viscous oils (Rodriguez et al., 2000; Skoczylas and Alhanati, 1998).

Appropriate motor cooling is critical for proper ESP operation. Temperatures in the motor need to be within materials operating range, which are usually limited by sealing materials, such as elastomers. Lower temperatures also improve system reliability. According to the Arrhenius rule, equipment life is expected to reduce in half for every 18°C increase. Hence, proper heat transfer avoids the thermal failure of components and improves the system life.

LITERATURE REVIEW

The open literature was surveyed to evaluate how the industry approaches the heat transfer problem for ESP motors. The studies were divided into six different categories: hydrodynamic, thermal, CFD, internal, experimental, and improvement studies. The multidisciplinary nature of studying ESPs must be evident. Manufacturing, petroleum production, materials science, thermodynamics, fluid mechanics, and heat transfer are some of the knowledge areas required to understand an ESP system's characteristics and operational requirements fully. The following literature review focuses on analyzing ESP systems from a thermal standpoint.

The rule of thumb

The Artificial Lift Methods book by Brown (1980) is a compendium of design guidelines, examples and troubleshooting instructions for various artificial lift systems. For instance, Volume 2b mentions insufficient fluid movements in the well as a possible cause for motor failure and recommends a fluid velocity of ¾ to 1 ft/s. This is probably the origin of the popular 1 ft/s rule of thumb widely used in the industry.

CFD

Rodriguez et al. (2000) studied the use of shrouds to accelerate fluids past the motor for viscous oils by using a CFD approach. It was found that the 1 ft/s rule of thumb is not valid for the simulated conditions, which required a fluid velocity of 2.8 ft/s to obtain proper heat transfer. More recently, Prasad (2019) used CFD to study how ESP systems behave in Steam-Assisted Gravity Drainage (SAGD) applications, focusing on no-flow events. The main challenge in SAGD is the multiphase flow in the presence of steam, which might present vapor-flashing. The study acknowledged the difficulty of modeling multiphase flows with a CFD approach and stated that the results are only qualitative. The highest temperature points were not at the bottom but the sides of the ESP motor due to liquid boiling (Prasad, 2019).

Thermal Models

The first identified thermal model for ESPs in the present study was developed by Powers (1994) while studying depth limitations on the operation of ESPs. Deep reservoirs with low pressures require higher pump heads, generating more heat while operating at higher temperatures due to the geothermal gradient. Powers (1994) decomposed the motor temperature rise into three components: fluid temperature rise after absorbing motor heat (ΔT_f), skin temperature rise to transfer heat to fluids (ΔT_S), and windings temperature rise to transfer heat to the skin (ΔT_W). Powers considered the coupled behavior of motor and pump and found that ΔT_f is proportional to the pump head and independent of flow rate for single-phase flow. In other words, this component is independent of the fluid velocity in the annulus.

Skoczylas and Alhanati (1998) improved the estimation of ΔT_S by extending it to the laminar flow regime and using homogeneous gas-liquid mixtures heat transfer correlations. Fully developed laminar flow conditions require higher temperature rises to transfer heat, resulting in an over-conservative estimate. Later, Betonico et al. (2015) rediscovered this model and improved it by considering developing laminar conditions.

Some characteristics of two-phase ESP motor heat transfer were ignored by previous authors. The overall heat transfer coefficient is most likely dependent on the distribution of liquid and gas phases around the motor (i.e. flow pattern). This is because heat transfer with the liquid phase requires less temperature differences for the same amount of energy. Additionally, since the fluid mixture is below bubble point pressure, it is saturated and adding heat will generate additional vapor. At medium heat fluxes, vapor generation aids heat transfer, lowering the temperature difference required to cool the surface in comparison with forced convection. At high heat fluxes, an insulating vapor film will be formed on the surface, requiring much higher temperatures to cool the surface down. This critical heat flux phenomenon is known in the heat transfer literature as boiling crisis, burnout, and other names. It is characterized by an unstable temperature rise for heat controlled surfaces where higher temperatures generate more vapor which further insulates the surface (Hewitt, 1998). It is currently unknown to what extent critical heat flux phenomenon will be significant in oil and gas applications. Previous heat transfer studies in the oil and gas industry focused on pipelines, where heat losses are spread through large areas and hence present low heat fluxes compared with ESP motors' values.

Internal motor model

In 2010, a collaboration between Los Alamos National Laboratory, Baker Hughes Centrilift, and Chevron Energy Technology Company resulted in a state-of-the-art thermal model for induction motors (Jankowski, 2010). This transient lumped-parameter model predicts temperature distribution inside the motor and indicates areas where the heat transfer is most inefficient from an entropy generation perspective. This approach was used to identify potential improvements in motor design, simulate different configurations, and perform a cost-benefit analysis on enhancement alternatives. A prototype was built, and the model was validated with lab and field experimental results (Bough et al., 2014). Field data was from Rangeley, Colorado, with a Bottom Hole Temperature (BHT) of 160 °F and from Canada in a Steam Assisted Gravity Drainage (SAGD) application with a well BHT of 175 °C.

Experiments

ConocoPhillips and Schlumberger jointly tested an ESP system prototype at C-FER technologies for SAGD applications in temperatures up to 250 °C (Noonan et al., 2010). This effort continued, and a similar paper was published in 2012 (Waldner et al., 2012). Both studies presented ESP motor skin temperatures at three different locations, while the latter also measured and reported motor windings temperatures. Both studies presented slightly higher temperature in the axial mid-motor section, which indicates either an axial non-uniform heat flux distribution on the motor or a problem with thermal probes placement. It is worth mentioning that temperature measurements in a heat-transferring environment are technically difficult for two reasons. The most obvious is that temperatures are different at each point since a temperature difference is required to transfer heat from one point to another. The more nuanced reason is that the temperature probe material is different from its surroundings, affecting the temperature gradient vs. heat flux relationship and effectively changing the temperature at the measured point. Not only the probe's position is essential, but also its orientation and contact resistance. These effects probably influenced the data obtained by Noonan et al. (2010) and Waldner et al. (2012), mainly because of the higher temperature in the axial middle of the motor skin. The experimental data on these studies was not evaluated using any thermal model.

Hydraulic studies

More recent studies have focused on the problem of gas-locking (Noonan et al., 2014; Ye et al., 2019; Prasad, 2019). No flow events are important because all the electrical input power in the system is being converted to heat at the motor and the pump, which could cause severe damage to the system (Ye et al., 2019). Noonan et al. (2014) performed experimental tests on an ESP pump monitoring pressure and temperature at every few stages. The tests reduced the pump inlet pressure and monitored the system's behavior as the pump approached saturation pressure values, increasing the amount of vapor in the pump. Interestingly, the first stages were the ones with the most loss of head, which needed to be compensated in the later stages. This asymmetry could be used to monitor ESP operation and assist in detecting no-flow events.

Thermal transients are remarkably slow during operations, and waiting for motor temperatures to rise above alarm levels during a gas-locking event might result in damage to the ESP as most of the heat is dissipated at the pump on these conditions (Ye et al., 2019). An alternative would be to monitor operating conditions and detect no-flow events before temperatures rise to damaging levels. An interesting strategy for this is possible by considering the coupled behavior of the multistage pump and the motor. With a few assumptions, it is possible to get instantaneous measurements of pump efficiency divided by flow rate (Camilleri et al., 2018), which could be used as a real-time measurement of either efficiency or flow rate.

Improvement studies

The connection between motor temperature and reliability makes it possible to obtain field results without completely understanding the ESP heat transfer problems. A recurrent approach in the industry has been to improve temperature ratings of ESP motor internal components and validate a reliability increase in the field (Refaie et al., 2013; Graham et al., 2017; Mansir et al., 2018; Caridad and Shang, 2019). This approach focuses on the commercial point of view, looking at immediate gains. In the long run, this approach could present significant problems. The industry would benefit from a fundamental understanding of heat transfer problems, even at the basic level.

SUMMARY

Two facts stand out from the literature review: the prevalence of the 1 ft/s rule of thumb and the lack of a standard heat transfer model. Very few studies worked on developing a heat transfer model for ESP motors. The most comprehensive model is the one of Jankowski et al. (2010), which focuses on modeling heat transfer in the internal parts of the motor. Although it provides rich results, the model is very computationally intensive and not very intuitive, especially for those without considerable experience in heat transfer. Additionally, even though the equations are published in the paper, the calculation procedure is complex, and the code is not available to the public, which presents another barrier to using the model. This becomes a problem for ESP system designers and operating engineers, as predicting the motor operating temperature is just one of many tasks they perform, and hence, they cannot spend too much time trying to understand a tool that will solve only one problem. There is a limit on how much overhead a useful model can have.

The underlying physics of ESP motor heat transfer is complicated. At the first level, an energy balance on the motor dictates how much heat is generated, and another balance determines the temperature increase on the fluid side. This first level of complexity already presents difficulties, as a measurement of the instantaneous flow rate of each phase is not always available, especially when the system is operating in unsteady conditions. At a second level, heat transfer needs to be taken into account. The heat path is from the motor windings, where heat is generated, to the motor wall, then to the produced fluids, and then possibly from the fluids to the well surroundings. At each point in this path, if the generated and incoming heat is higher than the removed heat, the local temperature at this point will increase. Conversely, the local temperature will decrease if more heat is removed than produced and injected. This temperature dependence on the position already presents difficulty from an experimental side, as the location and orientation of the probe need to be carefully considered when evaluating the problem. These difficulties are amplified in a multiphase flow environment, as the heat transfer will be dependent on flow patterns, which might present a transient behavior. All these model complexities have been simplified in the industry to the 1 ft/s rule of thumb. A more careful analysis would use thermal models to obtain temperature rise values for each ΔT component.

Many of the experimental works were not evaluated with a heat transfer model. Even the simple model proposed by Powers (1994) could serve as a very good tool to better understand the experimental results and get improved insights into previous studies. For instance, Waldner et al. (2012) acknowledge the fact that temperature measurements are very dependent on position and attributed this positional dependence of temperature and lack of proper thermal contact for their low readings of temperatures past the motor, at the pump intake, which was only 2°C higher than the casing inlet temperature. However, more careful examination using the Powers (1994) model using efficiencies of 60% for the motor and pump and the provided thermodynamic property values results in a temperature increase of approximately 2°C, which is consistent with the experimental data.

Powers (1994) divided temperature rise into three components: temperature rise in the fluids after absorbing heat from the motor, temperature rise on the skin to transfer heat from the skin to fluids, and internal temperature rise. This division is particularly interesting because it allows for simple models to identify sources of high-temperature rise in the motor.

The first component corresponds to the first level of complexity from the problem. It is obtained using energy balances at the motor and the fluids and depends on flow rate, amount of heat generated, and the fluids' thermal properties. This temperature rise increases in the axial direction as the fluids absorb more heat. Since the generated heat is proportional to the pump's power, this component is ultimately a function of the pump's head (Powers, 1994). Hence, the only alternative to reduce this is to decrease the amount of generated heat by lowering the pressure rise at the pump, which is determined by IPR/OPR relationships.

The second component corresponds to the heat transfer from the surface to the fluids. Correlations proposed by Skoczylas and Alhanati (1998) or Betonico et al. (2015) could be used for single-phase flow. This temperature increase is larger for laminar flows and depends on velocity for turbulent flows or laminar flows in the developing region. In other words, increasing the velocity is only effective if it results in turbulent flow in the annulus space or delays the development of the laminar thermal boundary layer enough to prevent the flow from being fully developed at the end of the motor. This temperature rise is more complex to determine than the first one, especially for multiphase flows. However, it is expected that reasonable estimates might be obtained by modifying existing correlations and using a mechanistic model.

The third component is the internal temperature rise, and it depends only on internal components. Simulations using the Jankowski et al. (2010) model will likely present very good results, as this model was already validated with field trials. Small modifications might be introduced to take into account changes in boundary conditions. Changes in the motor are required to reduce this component. Examples include increasing the fluid contact area using fins, internal channels circulating oil, etc. (Bough et al., 2014).

CONCLUSIONS

Understanding ESP motor heat transfer is challenging. The system and physics complexities make obtaining meaningful results hard. Previously, the industry simplified the problem using a 1 ft/s velocity in the annulus rule of thumb. General considerations that improve the understanding of this rule's limitations were presented. An alternative approach that divides the motor temperature rise into three components was presented, and general guidelines on how to estimate and minimize them were given. This model attempts to be simple enough to provide general directions of the motor temperature behavior in different scenarios. For instance, lowering the flow rate reduces the generated heat and decreases the first component and will probably affect the second component; lowering flow area to increase fluid velocity (i.e., using a shroud) will only affect the second component. It is expected that this simple model can bring more physical intuition to ESP motor designers and operation engineers, allowing them to find solutions to their problems quickly.

One of the drawbacks of this model is that it was mainly developed for single-phase flow. The first and second temperature rise components need to be adapted to model two-phase flow conditions. Heat transfer coefficients will depend on flow pattern and fluid velocities reaching the motor, which is dependent on upstream conditions and how the flow transitions from a pipe to an annulus geometry. It is unclear if vapor generation effects will be significant for this application. Our group will continue developing this model so that it can also be employed in two-phase flow conditions.

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