Cureus Journal of Engineering

Open Access Original Article

Deliquefy a Deep Gas Well with a Recirculation Electric Submersible Pump System

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Received 04/15/2025
Review began 04/29/2025
Review ended 05/05/2025
Published 06/27/2025

DOI: https://doi.org/10.7759/s44388-025-04971-5

Abstract

As a gas well dewatering artificial lift system, the electric submersible pump (ESP) is prone to gas interference, leading to such failure such as gas lock. Effective gas separation is essential to the efficient operation of ESPs. However, current studies do not concern the calculus of motor cooling. Taking a deep gas well in the Tarim Basin as a case study, this paper designs an inverted shroud to separate gas from well fluid. To analyze the workings of the inverted shroud, an equivalent virtual well is set up in a commercial software. The predicted pump intake and discharge pressures from the simulation are in good agreement with measurements from downhole sensors, proving high efficiency in gas separation with the inverted shroud, while also lending confidence to further studies. To improve the cooling of ESP motor seated below the shroud, a recirculation ESP system is also proposed. Numerical simulations indicate that two capillary tubes with an inside diameter of 10.5 mm are sufficient for motor cooling. These findings are helpful to boost ESP applications in deep gas well deliquifications.

Categories: Fossil Fuel Energy, Design and Manufacturing, Petroleum Engineering
Keywords: inverted shroud, encapsulated esp, gas well dewatering, software simulation, modelling

Introduction

Electric submersible pumps (ESPs), as an economical and effective artificial lift system, have been widely used in oil production [1]. However, its usages in gas well dewatering are still in the trial stage. Gas well deliquification with ESP involves separating the gas-liquid mixtures by deploying a downhole separator [2]. The separated liquid is rapidly expelled up the tubing string by multistage centrifugal pumps, with separated gas flowing naturally towards the casing head. In terms of separation mechanism, existing downhole two-phase separators fall into two categories: gravitational and centrifugal separators [3].

Gravitational separators are devices or tools that use the natural or gravitational force for gas-liquid separation [4]. In one study, an automated experimental separation facility was set up [5]. Both packer-type centrifugal downhole separators and a basic gravity-type downhole separator without the centrifugal part are evaluated. Separation efficiency is close to ideal (100%) for liquid rates up to 500 barrels per day (BPD) (79.5 m^3/d) for both separators. The efficiency decreases slightly at higher liquid rates, but stays above 80%. This decline in efficiency is more noticeable for the gravitational separator compared to the centrifugal. It is sharper for Gas-Liquid Ratio (GLR) higher than 300 standard cubic feet/standard barrel (SCF/STB) (53.4 m^3/m^3). The centrifugal separator provides a more stable flow rate with less fluctuation compared to the gravity-type. However, centrifugal separators have serious difficulty with slug-flow pattern, beside the moving parts, which increases the maintenance frequency and consequently the costs [6]. On the other hand, gravitational separators like inverted-shrouds have the advantages of low front investment and operating costs, without moving parts or reducing a cross-sectional area [7].

Gas anchors and shrouds are among two main types of gravitational separators. Gas anchors can be set either above or below the fluid-entry zone [8]. The shroud is a type of natural downhole gas separator. Shrouds can sub-divided into poor boy and packer type, and be placed below the producing horizon or above the well perforations [9]. Marcel and others use experimental methods to study the separation efficiency of inverted shrouds at inclinations of 450 and 600 [10]. Delgado and others introduce a case study of a shrouded ESP, with two stages separation in 7 inch casing, resulting in the pump intake pressure down to 220 psi (1.5 MPa) [11]. Zabala et al. designs an encapsulated ESP system with a double stage of gas separation [12], to reactivate a very gassy and depleted well, where none of the artificial lift systems (sucker rod lift, Progressive Cavity Pump (PCP) and ESP) can operate with good results. The first stage of gas separation consists of a configuration of different equipment used on sucker rod lift system. The second one makes up of a vortex ESP gas separator and a gas-handler pump in the ESP string. Lopez and others use experimental methods to study the impact of gas-liquid flow velocity on separation efficiency in inverted shrouds with different inclinations [13]. In a high GLR CO_2 application, a multi-phase encapsulated production solution is installed to separate the gas from the liquid in the wellbore [14]. Bridges et al. introduces an ESP recirculation system in an artificial sump [15]. Reid et al. presents the application of an ESP recirculation system set below the perforations in a 5.5 inch casing.

However, to be best of the authors' knowledge, preceding studies do not concern the calculus of ESP motor cooling. In view of this, current work takes a deep gas well from Tarim oilfield as an example, designs a ESP system with an open-ended inverted shroud. And its equivalent virtual well is set up in a commercial software. Facing insufficient cooling of ESP motor seated below the shroud, a shrouded ESP with a recirculation system is proposed. Finally, to validate the viability of the recirculation system, the calculus of flow rates under various pressure boost are performed with a commercial software. The findings of this paper has significant prospects for improving the application of ESP in gas well dewatering.

Materials And Methods

Technical principle of gravity-driven downhole separators

Downhole Separators in a Natural Sump

The most common method of gas avoidance is a shrouded ESP system set below the perforations, with an open-ended pipe placed around the ESP equipment to force fluid flowing below the motor through the inside of the shroud before entering the pump intake [14], see Figure *1a* for detailed schematic. Bridges et al. refer to it as a shrouded ESP in natural sumps (or rat holes) [16]. Using the rat hole as a sump for the pump has usually been very successful in avoiding gas. Similar to the shrouded ESP, a long dip tube pipe connects to the bottom of the shroud assembly to allow the pipe to seat below the perforations instead of the ESP assembly, see Figure *1b*. This system is used to allow more annular area for separation, or in cases where the wellbore below the perforations does not have enough space for the ESP system. If the wellbore has adequate room below the perforations in the rat hole, a recirculation system can be used. Since there is no natural flow rate occurring past the ESP motor, a small recirculation pump and capillary line are used to bypass some of the flow below the motor for cooling purposes (Figure *1c*).

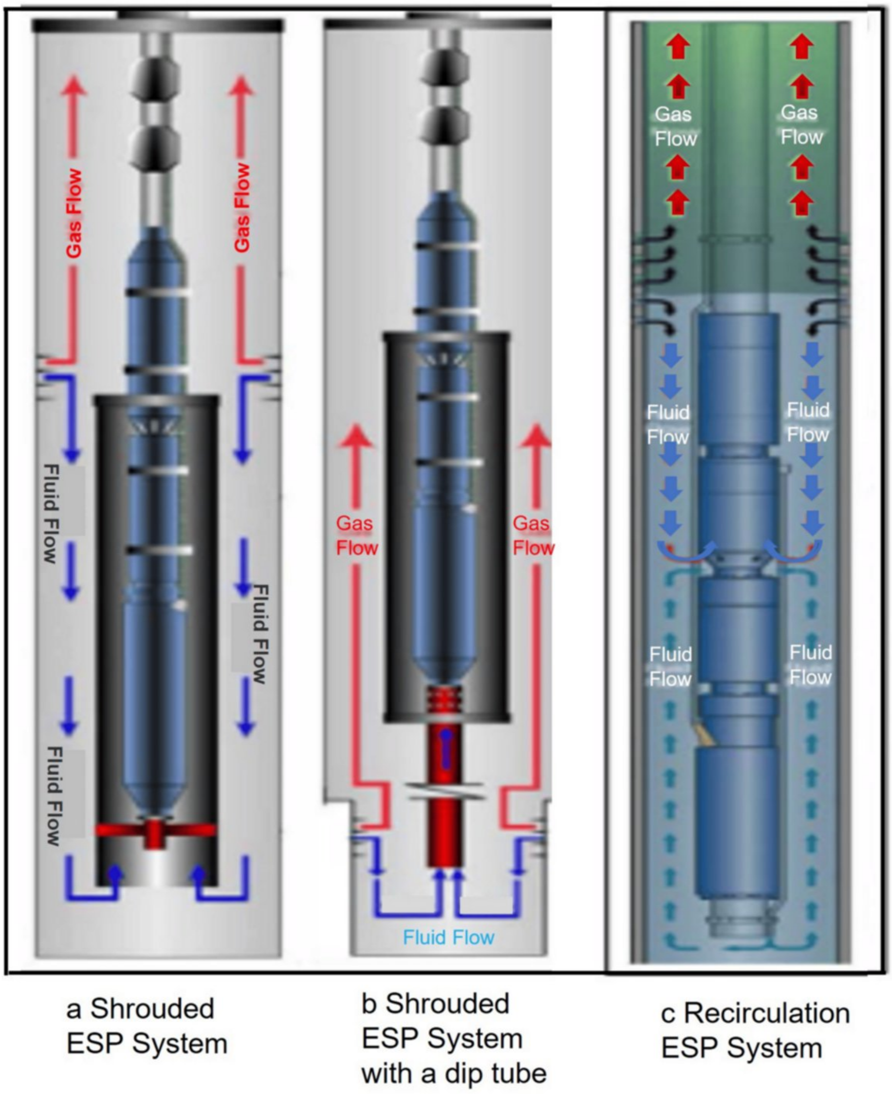

FIGURE 1: Schematic of two-phase separator below the well perforations (adapted from B. L. Nicholson et al., SPE 194396)

ESP, Electric submersible pump

Downhole Separators Above Well Perforations

There are primarily two forms of downhole separators placed above well perforations: poor boy and packer style. Poor boy is one form of packerless downhole separators, which apply gravity-based gas separation principles. Saponja et al. provides a detailed description of its enhanced design and field implementation [3]. Figure *2* illustrates poor boy and packer style separator flow path and typical design configurations. Poor boy separators are commonly based on the same design principles of a concentric pump intake dip tube inside a tubular mandrel, with side entry slot or port intakes and gas vents to the well's casing annulus. Gas separation occurs in an inner cross-sectional area formed inside the separator with its pump intake dip tube as shown as A1 in Figure *2*.

Packer style separators require a packer or cup seals (in conjunction with a tubing anchor catcher) for directing all multi-phase fluid flow through the separator, and for discharging at the top of the separator into the casing annulus. A pump intake dip tube port is positioned just above the packer/seal to draw in degassed liquid from the casing annulus. Gas separation occurs in the casing annulus formed between the well's casing and the separator's outer mandrel as shown at A2 in Figure *2*. This separation annulus can be larger in cross-sectional area as compared to a poor boy separator's A1 separation annulus. This larger cross-sectional area can improve separation capacity and efficiency simply since there is more cross-sectional area (i.e., liquids travel downward at slower velocities). The fluid residence time in this separation annulus, as the liquid moves downwards to the pump intake, can also be beneficial for separation of gas if the volume is larger than one pump stroke. A major operational risk and downside of a Packer-Style separator is that solids can settle on top of the packer or cup seals and cause significant workover cost/risk (i.e., retrieval risks can be high). To control this risk, a solids separation accessory is commonly attached below the packer/seal and upstream of the gas separator.

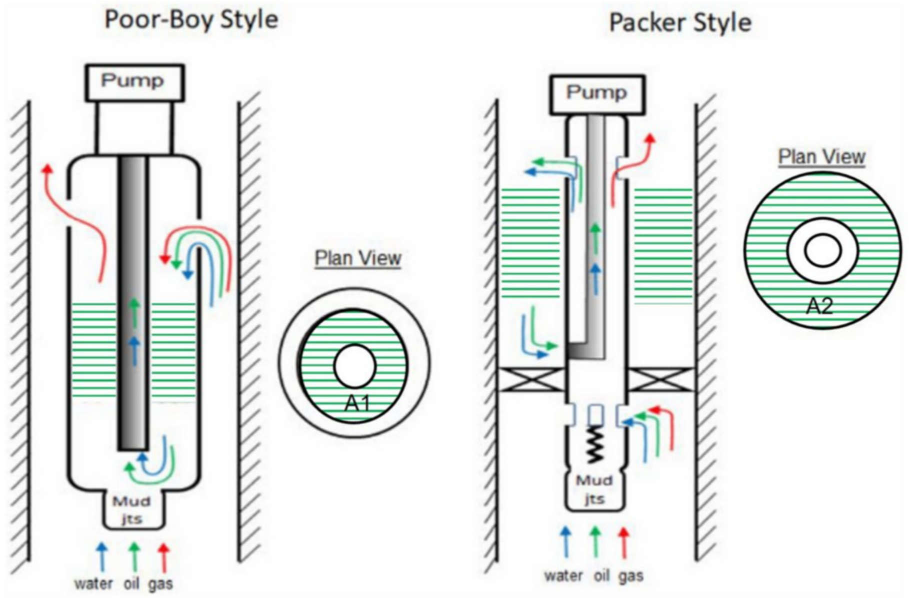

FIGURE 2: Poor boy and packer style downhole separator (from Jeff Saponja et al., SPE 209755)

Working Principles of a Shroud Type Downhole Separator

The working principle of a shroud type downhole separator is similar to that of an gas anchor. It is basically a gravity-driven separator. Figure *3* presents a schematic of an inverted-shroud type downhole separator placing above the well perforations, as happened in horizontal or deep wells. Gas liquid mixtures come out of the well perforations, travelling up the annulus between the shroud and the casing, as shown in section A of the diagram. The first gravity-driven separation takes place at the inlet ports, as seen in point B of the schematic. Gas-rich stream continues ascending through the casing, whereas a liquid-rich stream falls into the shroud. Some remaining gas is dragged into the shroud by the descending liquids. In the annulus formed by the shroud and the tail pipe, gas bubbles will separate if the liquid velocity inside the shroud is unable to drag them into the tail pipe. This gives rise to the second gravity-driven separation. The liquid will continue flowing downward until it reaches the tail pipe, represented by letter C in Figure *3*. In this section, the liquid-rich well stream changes direction [17]. This last change in flow direction facilitates the separation of solids, which will accumulate at the bottom of the shroud.

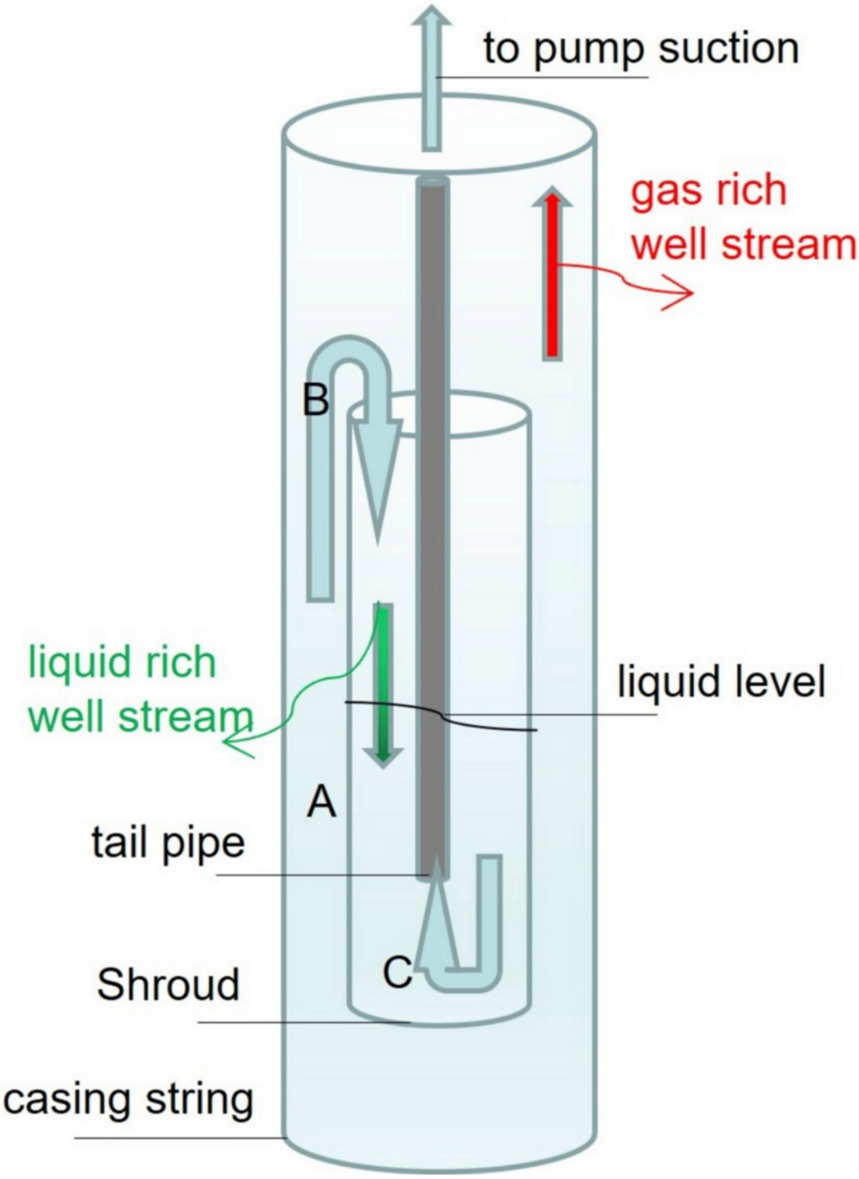

FIGURE 3: Schematic on workings of gravity-driven downhole separator

When a slug flow approaches an inverted shroud, the above mentioned first and second separations will occur sequentially, whether the slug body or liquid film region approaches the shroud intake. If the slug body is at the intake (see point A in Figure *4a*), part of the gas will be separated from the well fluid and continue flowing upward along the original path. The remaining bubbles are carried away by the liquid into the separator and undergo the secondary separation at Point B. When the liquid film region is at the intake (Figure *4b*, point A), this fast-moving Taylor bubble will continue its upward trajectory. And therefore this Taylor bubble undergoes the first separation. The liquid film and following slug body fall into the separator and experience the secondary liquid-gas separation.

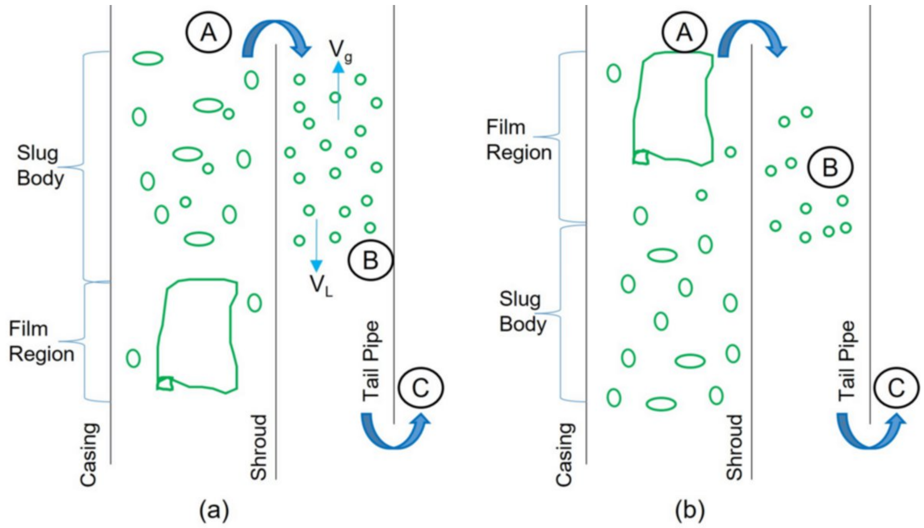

FIGURE 4: Schematic of an inverted shroud under slug flow approached by (a) slug body and (b) film region

In Figure *4a*, VL is the downward velocity of the liquid in the annular formed by the shroud and the tail pipe; Vg is the rising velocity of the bubble (m/s), which can be expressed as [18]:

$$Vg = 1.53[\frac{g\sigma(\rho_l - \rho_g))}{\rho_l^2}]^{0.25}$$

Where: g is the acceleration due to gravity, m/s^2; σ is the surface tension, N/m; ρl is the density of the liquid phase, kg/m^3; ρg is the density of the gas phase, kg/m^3.

In field application [19], the inlet pressure at the gas separator can reach as high as 1000 psi under normal conditions. As the pressure increases, density of the gas also increases, resulting in a lower value for (ρl-ρg) and thus a reduction in Vg. This may explain why gas interference is more common and more severe in wells with high liquid levels.

To ensure that the gas is separated from the liquid-rich well fluid, the liquid phase velocity should be lower than that of the rising bubble, and the lower its value, the better the gas-liquid separation efficiency. According to field practices [14], to achieve a gas-liquid separation efficiency of 60%, this liquid velocity should be less than 0.15 m/s.

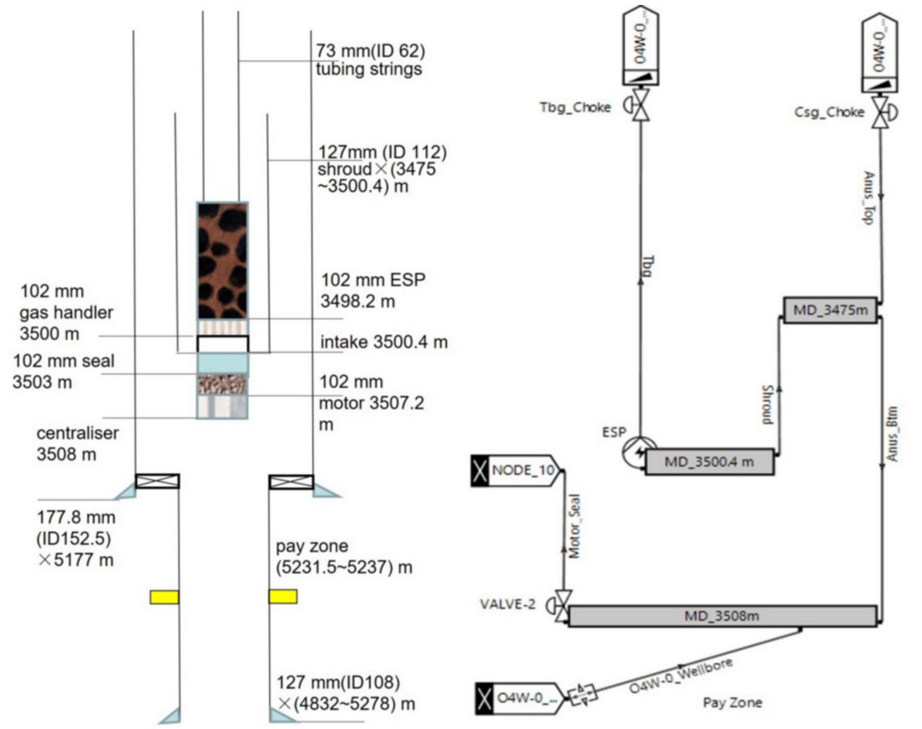

Fig. 5. Schematic of Inverted-shrouded ESP (left) and equivalent virtual model (right)

FIGURE 5: Diagram of inverted-shrouded ESP (left) and equivalent virtual model (right)

ESP, electric submersible pump

Deep gas well dewatering with inverted-shrouded ESP

Take Well YD102 from the Tarim Oilfield as an example. The well is a water-producing gas well, and the production casing is 7 inches [20]. If the liquid flow rate is low, this large casing will exacerbate the cooling of the motor. The schematic diagram with the ESP for Well YD102 is shown in Figure *5* (left), and its equivalent OLGA software model is shown in Figure *5* (right) [21]. The OLGA program is a commercially available software [22]. In Figure *5* (right), the formation fluid produced by the pay zone flows upward to the internal node "MD_3508m," along the flow path titled "O4W-0_Wellbore." At this internal node, the produced formation fluid can travel either to the internal node "MD_3475m" through "Anus_Btm" or to the closed node "NODE_10" through "Motor_Seal." However, since the opening of the valve "VALVE-2" is zero, the flow on the flow path "Motor_Seal", which represents the motor and seal, is blocked. The internal node "MD_3475m" represents the inlet of the shroud. Therein, the well stream can move either upward to the casing head or it can flow into the ESP through "Shroud." On the ESP pump model, the built-in "ALNAS ANA545 Version 1" is selected; the number of stages within the ESP is 368, and motor rotational speed is 3500 rpm.

Validation of the Virtual Well Model

The initial conditions of the model are as follows: the static liquid level is 2180 m, the reservoir pressure of the pay zone is 30.8 MPa, and the pressure coefficient is 0.59 MPa/100 m. The properties of the reservoir fluid produced: the gas-oil ratio is 15000 m^3/m^3, and the water content is 98%. Both the tubing head and casing head have a choke, with the same diameter being 8 mm, and the opening being 1. The running time is 1440 minutes. The comparison of the predicted and measured values of pump intake pressure and pump discharge pressure is shown in Figure *6*. It shows that as the pump starts up, the pump inlet pressure decreases gradually, and then fluctuates due to oscillation of the annular liquid level caused by the casing gas production [23].

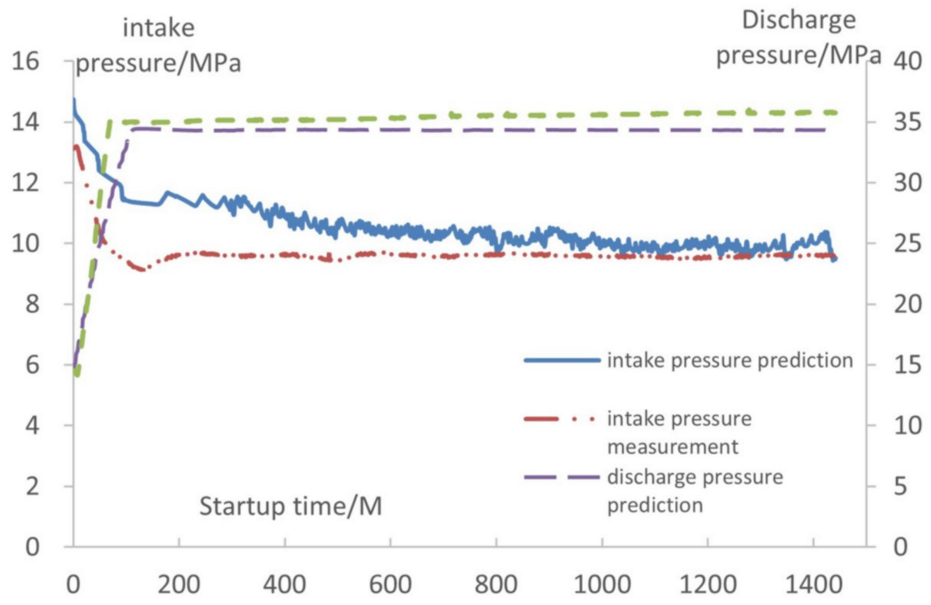

FIGURE 6: Trend plot of predicted and measured values for pump intake and discharge pressures

For the pump discharge pressures in Figure 6, it can be seen that when starting the pump, as the liquid level in the tubing rises, the pump discharge pressure increases continuously as well until the liquid surface reaches the wellhead, at which point the pressure reaches the maximum value and remains stable. Table 1 is a comparison of the prediction and measurement at the end of the simulation, and they are in good agreement. Therefore, this model can be used for further predictions.

Item	Liquid Production/($m^3 \cdot d^{-1}$)	Pump Intake Pressure/MPa	Pump Discharge Pressure/MPa	Pump Intake Temperature/℃
Prediction	40	9.92	35.56	98
Measurement	48	9.59	35.57	95

TABLE 1: A comparison between OLGA model prediction and measured values

Deep gas well dewatering with a recirculation ESP

Pitfalls of Inverted-Shrouded ESP

To ensure long-term run life of an ESP unit, the ESP motor needs to have adequate cooling. Therefore, the liquid velocity and liquid content at the motor location were retrieved from the simulation (Figure 7). From this figure, the liquid velocity (represented by the black dashed line) fluctuates wildly during the simulation, with an amplitude of (-0.4⊠1.4) m/s. The negative velocity indicates that the flow direction is opposite to the pipeline direction. On the other hand, the variation in the liquid content (represented by the red solid line) is 0.2⊠0.8, indicating that the periphery of the motor is a two-phase gas-liquid flow. Since the heat transfer of a two-phase gas-liquid flow is much lower than that of single-phase liquid flow. Moreover, liquid velocity fluctuates violently, accompanied by positive and negative directional gas slugs. Additionally, there are reports in the literature that the cooling effect of this submerged motor is poor [17]. This conclusion is also verified by the continuous rise of the measured temperature at the pump intake, as the pump intake is only 3.2 m above the motor.

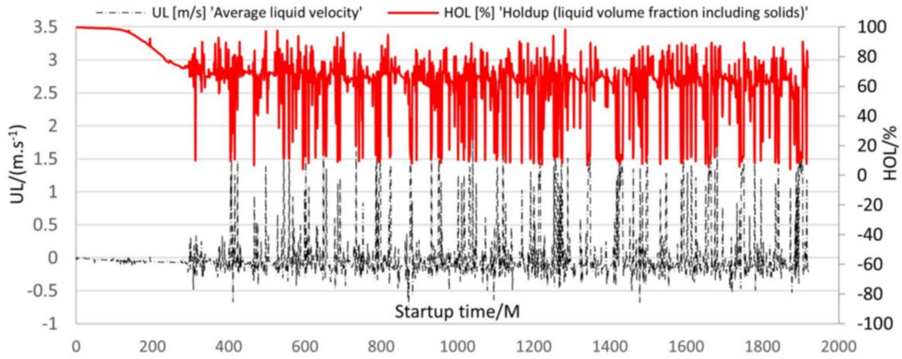

FIGURE 7: Evolution of liquid velocity and liquid content outside the motor

Results

Recirculation ESP system

To mitigate the hazard of inefficient motor cooling, researchers [18-20] have proposed a recirculation ESP system with an inverted shroud, as shown in Figure *8*. In this figure, the well fluid is represented by the blue arrow. It flows upward along the annular space between the production casing and the shroud. At the shroud inlet, the gas-rich well fluid continues to move upward, and the liquid-rich stream (represented by the red arrow) flows downward the shroud to the pump inlet.

The recirculation ESP system described herein differs little from a standard ESP unit except for the addition of the following: the recirculation pump, the recirculation tube, the connector for recirculation pump and tube. The recirculation pump serves as the intake for the unit and should consist of as few stages as possible in order to minimize the horsepower added to the overall system. The recirculation pump must be staged to generate sufficient pressure boost to overcome frictional losses down the recirculation tube. The recirculation stage must be volumetrically larger than the lift pump stage to produce enough excess fluid to be circulated past the motor for cooling purpose. Installation procedures of this system are as follows: ⊠ Install the shroud; ⊠ Lower the ESP unit with the circulation pump to the predetermined depth inside the shroud; ⊠ Hang the hanger on the top of the shroud.

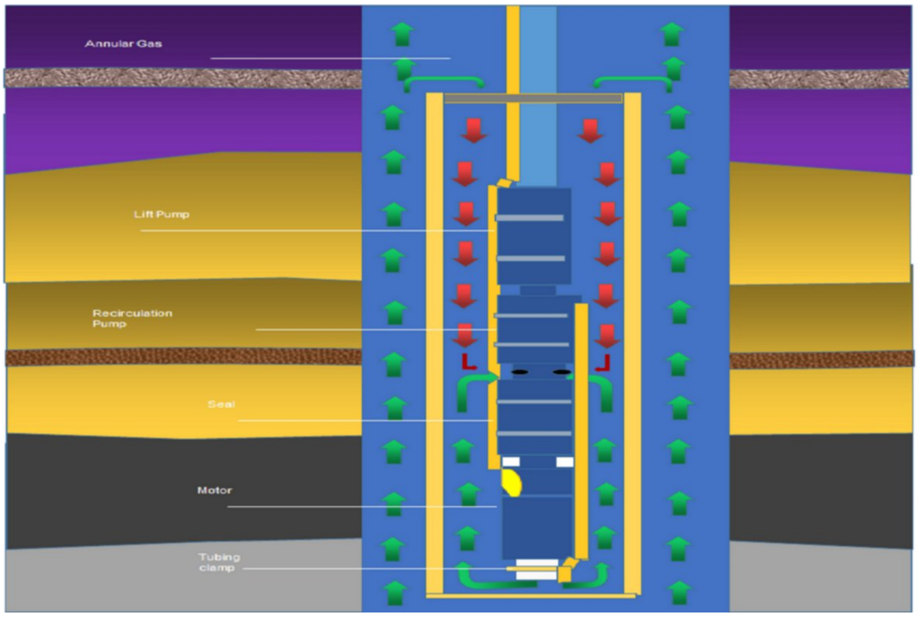

FIGURE 8: : Diagram of a recirculation ESP system in an artificial sump ESP, electric submersible pump

ESP, electric submersible pump

Based on this schematic diagram, and combined with the actual well conditions of the well in the Tarim Oilfield, an implementation of this canned motor unit is framed in Figure 9 (left). The commercial software OLGA is used for modellng (see Figure 9 (right)). In Figure 9 (right), the well fluid produced from the reservoir "O4W-0_Reservoir1" flows all the way to the internal node "MD_3470m" through the annular pipeline "Anus_Btm". At 3470 m, one part continues to flow to the casing head up the annulus "Anus_Top," and the other part of liquid-rich well fluid flows to the internal node "MD_3490m" through "Shroud_Up." At 3490 m, part of the liquid is transported to "Valve_Pt" by the "ESP-1." The other part, after being pressurized by the recirculation pump "BOOST_1," flows through the capillary tube "RecConduct" to 3512 m, and then returns to 3490 m through the annulus "Shroud_Mid." During this process, the ESP motor is forcibly cooled. The pipeline "Shroud_Dn" represents the sands settling pocket.

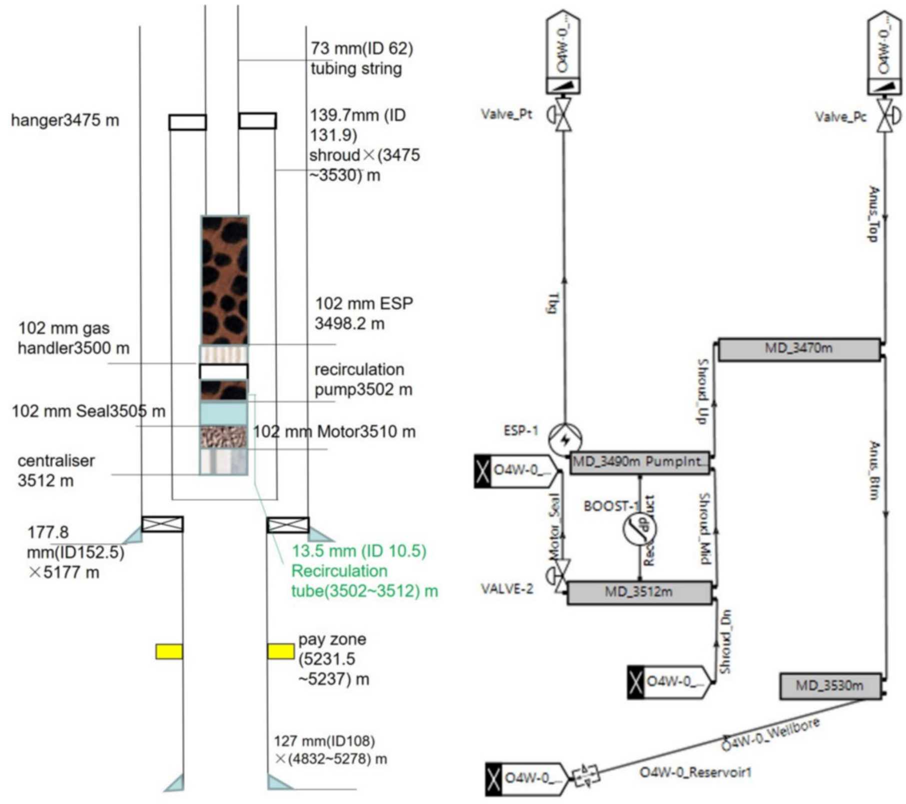

Fig. 9. Diagram of recirculation ESP system (Left) and equivalent software model (Right)

FIGURE 9: Diagram of recirculation ESP system (left) and equivalent software model (right)

ESP, electric submersible pump

Assuming the inside diameter of the slim recirculation tube outside the motor is 10.5 mm, the software model in Figure 9 (right) is used to simulate the liquid velocity outside the motor under various pressure differences boosted by the recirculation pump "BOOST-1." The sensitivity results are shown in Table 2. From this table, for various daily liquid productions, the increase in pressure generated by the recirculation pump has the same effect on the liquid velocity. If the pressure boosted by the recirculation pump is as low as 2.8 MPa, the liquid velocity passing through the motor reaches 0.15 m/s for two different liquid productions. In this way, if two capillary tubes with an inner diameter of 10.5 mm are connected in parallel, they can meet the industry requirement of 0.30 m/s for motor cooling. Therefore, this configuration of deep gas well dewatering with an encapsulated ESP is feasible.

Pressure Boost by Recirculation Pump/MPa	Daily Liquid Production/m 3	2.8	5	7.5	10
33		0.15	0.2	0.25	0.29
56		0.15	0.2	0.25	0.29

TABLE 2: Liquid velocity around motor under various pressure boost and well production

Discussion

The proposed ESP system with a recirculation pump can cool the motor sufficiently, in comparison with the inverted-shroud ESP system. The liquid velocity passing through the motor reaches 0.15 m/s following modeling of two separate liquid flow rates. Therefore, this configuration of an encapsulated ESP is feasible for gas well dewatering. The downhole recirculation system is selected over a traditional shroud for the purpose of forcing cooling fluid below the motor. It is necessary to select a recirculation pump with a higher flow rate than the lift pump, because the recirculation pump must move more fluid volume. Ample stages must be included in the recirculation pump to produce sufficient pressure at its discharge, so as to overcome the frictional drag that occurs inside the recirculation conduit.

The installation procedure of the ESP system with recirculation only vary slightly from normal ESP installs. The only change is that the motor/seal/lower pump must be lifted out of the well in order to attach the recirculation conduit. The workover rig's draw-works must be sufficient to accomplish this stroke, or installation could take much longer. Normally, the recirculation conduit assembly only adds about an hour to the ESP installation.

The proposed ESP system has the strength of power saving and a long run life. However, the recirculation ESP system has the disadvantage of a complex downhole installation, entailing both a lift and recirculation pump. For field applications and potential future research directions, the concept proposed in this study needs to build a prototype and make field tests.

Future works

Future studies might delve into: Parameter Optimization: Experimenting with variations in shroud geometry, material properties, or installation depths to further optimize gas-liquid separation. Long-Term Field Performance: Collecting extended operational data to assess wear, maintenance requirements, and overall reliability under diverse well conditions. Real-Time Monitoring and Adaptive Control: Integrating sensor data with simulation-driven models to create adaptive control systems that respond dynamically to changes in gas-liquid ratios in real time. Scalability and Applicability: Evaluating whether similar design principles could be applied to other artificial lift systems or wells with different geological challenges.

Conclusions

Use a water-producing gas well in the Tarim Oilfield as a case study. First, the configuration of an inverted-shrouded ESP unit is proposed, and its equivalent virtual well is set up. Secondly, to mitigate insufficient motor cooling by two-phase mixtures, a recirculation ESP system is presented. Its full-scale software modelings verify that liquid velocity conforms to industry standards. The findings of this study has a promotional effect on embracing ESP in deep gas well dewatering. Based on this, the following three conclusions are drawn:

(1) An appropriately configured inverted shroud can achieve efficient downhole gas-liquid separation.

(2) Placing the submerged motor in the gas-liquid mixture flow outside the shroud is not conducive to its adequate cooling.

(3) Two capillary tubes with an inside diameter of 10.5 mm are sufficient for motor cooling.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

Concept and design: Faqing Wang, Fangzhi Wang, Bao Zhang, Deyou Qin, Jun Yi, XiaoXun Gao

Acquisition, analysis, or interpretation of data: Faqing Wang, Fangzhi Wang, Bao Zhang, Deyou Qin, Jun Yi, XiaoXun Gao

Drafting of the manuscript: Faqing Wang, Fangzhi Wang, Bao Zhang, Deyou Qin, Jun Yi, XiaoXun Gao

Critical review of the manuscript for important intellectual content: Faqing Wang, Fangzhi Wang, Bao Zhang, Deyou Qin, Jun Yi, XiaoXun Gao

Supervision: Faqing Wang, Fangzhi Wang, Bao Zhang, Deyou Qin, Jun Yi, XiaoXun Gao

Disclosures

Human subjects: All authors have confirmed that this study did not involve human participants or tissue. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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