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Key Structural Design of a Downhole Variable-Angle Hollow-Shaft Turbine Generator

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Abstract

To address the insufficient wide-flow adaptability, limited structural integration, and restricted tool passability of downhole turbine power generation systems, a downhole variable-angle hollow-shaft turbine generator system is proposed. The system consists of a guide vane, a variable-angle turbine, a hypoid gear adjustment mechanism, and a hollow-shaft outer-rotor permanent magnet generator. Based on blade design theory, velocity triangle theory, and isentropic flow theory, the key parameters of the guide vane and turbine are determined, and 14 attack-angle models ranging from 0° to 90° are established. A hypoid gear mechanism is designed to realize synchronous angle adjustment of multiple blades, and a hollow-shaft outer-rotor permanent magnet generator is developed to achieve compact integration of the turbine, transmission mechanism, and power generation unit, providing a reference for the optimization and engineering application of downhole turbine power generation devices.

Keywords

Downhole Turbine Power Generation; Variable-Angle Turbine; Hollow Shaft; Hypoid Gear; Outer-Rotor Permanent Magnet Generato.

1. Introduction

With the rapid development of downhole intelligent measurement and control technologies and the intelligentization of oilfield equipment, the demand for efficient, stable, and autonomous power supply in petroleum downhole devices has become increasingly urgent. Downhole turbine generators use the hydraulic energy of drilling fluid to drive turbine rotation, which further drives a permanent magnet synchronous generator to realize electromechanical energy conversion. This represents an important power supply method for downhole tools. Since such systems operate for long periods in complex environments characterized by high temperature, high pressure, strong vibration, and erosion by solid-laden media in deep wells, they face stringent requirements in terms of structural compactness, energy conversion efficiency, and operational reliability, resulting in considerable design and manufacturing difficulties [1]. Therefore, in addition to the optimization of the electromagnetic structure and operating parameters of the generator, the mechanical structure of the turbine, blade geometric parameters, and turbine–generator matching design are also key factors affecting the output performance of the system [2]. At present, scholars at home and abroad have conducted certain studies on downhole turbine power generation technology; however, research on variable-angle turbine power generation systems remains relatively insufficient, with related achievements mainly concentrated in the fields of aerospace, wind power generation, and hydraulic machinery [3–4].

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Currently, extensive research has been carried out on downhole turbine generators by domestic and international scholars. Li Fei et al. [5] analyzed the coupling relationship among rotational speed, torque, current, and voltage, and investigated the effects of drilling fluid flow rate and load conditions on the output characteristics of a permanent magnet turbine generator by combining simulation curves of the turbine and generator. Ji Ling et al. [6] optimized the turbine structure and predicted its power generation performance under the constraints of limited downhole space and special turbine blade design requirements. Rakshith Shetty et al. [7] developed an annular pump structure powered by an internal turbine to improve the insufficient cuttings return capacity of a single suction pump in horizontal directional drilling. Sun Jun [8], from the perspective of blade load distribution, optimized the blade design of a downhole turbine generator by combining the orthogonal test method with forward and inverse design approaches. Jia Chao [9] conducted simulation analysis and multi-parameter optimal matching research on generator performance under different operating conditions and structural parameters, and optimized the guide-vane structure of a downhole turbine generator based on the response surface method. These studies provide important support for improving the performance of downhole turbine generators. However, they mainly focus on the local optimization of individual components or specific operating conditions, and a systematic design method oriented toward wide operating-range adaptability and structural integrated matching is still lacking.

To address the insufficient wide-flow-rate adaptability of existing downhole turbine power generation systems, this paper proposes a downhole variable-angle hollow-shaft turbine power generation system and carries out the design of its key structures. Considering the complex downhole operating conditions and spatial constraints, an overall scheme centered on a variable-angle turbine is established. The basic dimensions of the guide vane are determined, and key parameters such as blade number, span, blade surface profile, and leading and trailing edges are optimized to improve hydraulic matching and energy conversion efficiency under different flow-rate conditions. Meanwhile, a hypoid gear transmission structure suitable for confined spaces and a hollow-shaft outer-rotor generator are designed, realizing compact integration of the turbine, transmission, and power generation units. This study can provide a theoretical reference for the structural design, performance optimization, and engineering application of downhole variable-angle turbine power generation systems.

2. Structural Design and Working Principle of a Downhole Variable-Angle Hollow-Shaft Turbine Power Generation System

The downhole variable-angle hollow-shaft turbine power generation system is mainly composed of a guide vane, a turbine, a hypoid gear adjustment mechanism, and a hollow-shaft outer-rotor permanent magnet generator. After being rectified by the guide vane, the drilling fluid acts on the turbine blades and drives the impeller to rotate. In addition to guiding the flow and improving the matching of the incoming flow, the guide vane also functions in turbine protection, structural support, and overall positioning. The mechanical energy output by the turbine is transmitted to the generator rotor through a magnetic coupling device, driving the rotor to rotate and cut the magnetic field lines, thereby generating an induced electromotive force and realizing the conversion of hydraulic energy from the drilling fluid into electrical energy.

From the perspective of structural design, the downhole variable-angle hollow-shaft turbine power generation system adopts a hollow-shaft configuration, which reserves a central passage for the penetration and deployment of other downhole tools. The turbine blades realize installation-angle adjustment through a hypoid gear mechanism, thereby ensuring power generation stability under different flow-rate conditions and avoiding interference with other downhole operations. The downhole variable-angle hollow-shaft turbine power generation system is shown in Fig. 1. Once the electromagnetic parameters of the generator are determined, the key to improving the output power of the system lies in enhancing the hydraulic efficiency of the turbine mechanism. Therefore, in this paper, the hollow-shaft outer-rotor generator is embedded into the variable-angle turbine structure, a guide vane is arranged at the inlet to improve the incoming flow conditions, and the turbine blade

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installation angle is adjusted by the hypoid gear mechanism. Compared with a conventional fixed-blade turbine, the variable-angle turbine can adjust the blade throat area by changing the blade installation angle, thereby altering the turbine flow capacity and realizing hydraulic matching and flow regulation under different flow-rate conditions. As a result, the turbine operating efficiency and power generation stability can be improved.

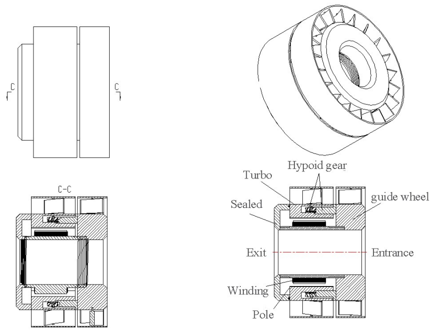

Fig. 1 Variable-Angle Turbine Power Generation System

3. Structural Design of Key Components

3.1 Structural Design of the Variable-Angle Turbine and Guide Vane

The inlet width of the guide vane is 15 mm, with an outer diameter of 80 mm, an inner diameter of 35 mm, and an axial length of 25 mm. A total of 15 guide blades with a certain curvature are arranged. The guide-vane blades are geometrically designed using the mean-line stacking method. The stacking position is set to zero, and together with the blade superposition position, it determines the spatial positions of the leading and trailing edges, as shown in Fig. 2. Before blade stacking design, the blade inlet angle α should be determined. This angle represents the geometric angle between the meridional plane and the leading or trailing edge of the blade. It directly affects the contact mode between the incoming flow and the blade as well as the flow-around characteristics, thereby changing the pressure distribution, lift–drag characteristics, and flow-guiding efficiency of the blade surface. [10–11]

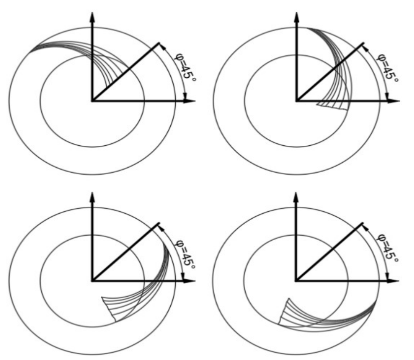

Fig. 2 Schematic Diagram of the Stacking Position

A rational design of the blade inlet angle can improve the fluid incidence conditions and reduce local impact losses and the risk of flow separation, thereby enhancing the flow-guiding capability of the guide vane and the overall efficiency of the rotating machinery. According to the design requirements and performance objectives of the guide vane, the leading and trailing edges of the blade can be appropriately twisted in the meridional plane to optimize the flow-matching relationship along the blade span, ensuring a favorable pressure distribution and flow stability on the blade surface. Fig. 3 presents a comparison of the blade structures when the guide-vane inlet angle α is 0° and 20°, respectively. Considering structural manufacturability, flow stability, and the need for model simplification, the guide-vane blade inlet angle is set to α = 0° in this study.

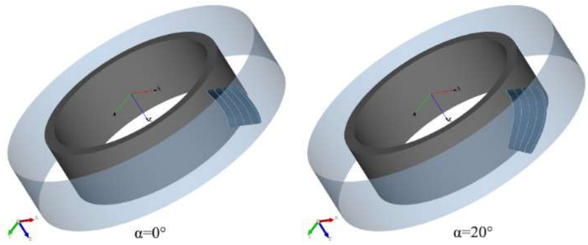

Fig. 3 Blade Inlet Angle

The hydraulic performance of the turbine is jointly affected by factors such as pressure distribution, flow-rate variation, fluid properties, and blade structural parameters. Considering that drilling fluid can be approximately regarded as a weakly compressible fluid under conventional downhole circulation conditions, isentropic flow theory [12] is introduced in the preliminary structural design stage of this study for idealized analysis, so as to neglect the effects of heat transfer, viscous dissipation, and local losses on the energy conversion process. Based on the prescribed pressure boundary conditions at the impeller inlet and outlet, the characteristic dimensions of the inlet and outlet are estimated using isentropic relations. During turbine operation, adjustment of the attack angle changes the pressure gradient, velocity distribution, and blade work capacity within the fluid domain, thereby affecting the hydraulic efficiency of the turbine. The corresponding isentropic relations are expressed as follows:

$$S(p_t, T_t) = S(p_l, T_l) \tag{1}$$

$$H(p_t, T_t) = H(p_l, T_l) + \frac{V^2}{2} \tag{2}$$

where S denotes the entropy per unit mass of fluid, p_t is the total pressure, T_t is the total temperature, p_l is the static pressure, T_l is the static temperature, H represents the enthalpy per unit mass of fluid, and V is the fluid velocity.

The main design parameters of the variable-angle turbine are listed in Table 1. In this study, the outer and inner diameters of the turbine are taken as key structural parameters. The design mass flow rate is 45 kg/s, the specific speed is 55, and the number of blades is set to 10. In the preliminary design, the fluid density is estimated as 7750 kg/m³, and the hub and shroud are arranged coaxially. Considering the viscous dissipation, local impact, and flow-passage losses that occur during actual flow, the ratio of actual efficiency to ideal efficiency, namely the isentropic efficiency, is taken as 72.5%. Meanwhile, an outlet velocity coefficient of 96% is adopted to correct the flow-passage outlet velocity, so as to characterize the influence of velocity variation and energy loss within the flow passage on turbine performance.

Table 1. Main Design Dimensions of the Turbine

Item	Value	Item	Value
Inlet hub diameter d_{H1}	70mm	Circumferential velocity u	186.0m/s
Inlet shroud diameter d_{H2}	70mm	Absolute velocity c	97m/s
Outlet hub diameter d_{S1}	100mm	Relative velocity w	209.8m/s
Outlet shroud diameter d_{S2}	100mm	Blade height h	18.2mm
Isentropic efficiency η_{ts}	72.5%	Outlet velocity coefficient ψ_N	96%

The turbine blades investigated in this study are straight-plate blades. To analyze the influence of variable-angle adjustment on turbine performance, the variable attack angle range of the blades is set from 0° to 90°, and 14 turbine models with different blade setting angles are established, as shown in Fig. 4.

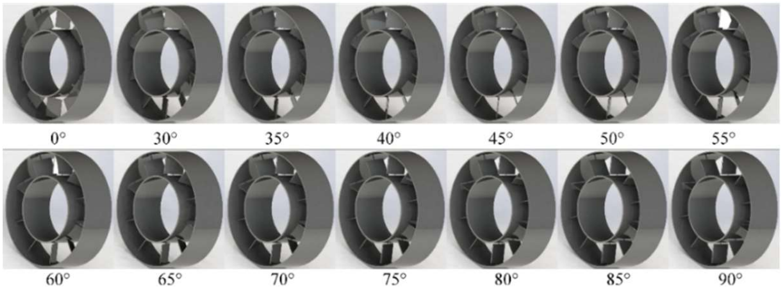

Fig. 4 Turbine Models with Different Blade Attack Angles

3.2 Structural Design of the Hypoid Gear

Hypoid gears are characterized by high load-carrying capacity, smooth transmission, and flexible spatial arrangement. Owing to their relatively large tooth-surface contact area, they can reduce the unit contact stress, mitigate tooth-surface wear, and improve transmission life. Therefore, they are widely used in high-load and high-reliability industrial transmission systems [13]. Since the tooth profile of a hypoid gear varies geometrically along the tooth width, parameters such as tooth thickness, tooth-surface curvature, and meshing contact state have significant effects on transmission strength and motion accuracy. Therefore, refined design of the tooth-profile parameters and tooth-thickness distribution is required.

In this study, the strength verification and parameter design of the gear pair are carried out under the constraints of the spatial arrangement and transmission requirements of the variable-angle adjustment mechanism. The gear pair adopts a constant slot-width configuration. The material is 18CrNiMo7-6, and surface hardening treatment is applied. The core hardness of the gear is not less than 25 HRC, with a tensile strength of 1200 N/mm² and a yield strength of 850 N/mm². ISO-VG150 lubricating oil is used for oil-jet lubrication. The transmission ratio is 8.87, the target tooth-root safety factor is set to 0.9, and the design life is 20,000 h. The basic design parameters of the gear are listed in Table 2.

Table 2. Basic Design Data of the Gear

Item	Value	Item	Value
Normal module m	0.7503mm	Number of teeth of Gear 1 z	8
Pitch diameter of Gear 2 (outer side) d_{e2}	70mm	Number of teeth of Gear 2 z	71
Pressure angle in the normal section α_n	20°	Profile shift coefficient of Gear 1 X_{hm1}	0.4500
Gear 1	Right-hand spiral direction (spiral tooth)	Profile shift coefficient of Gear 2 X_{hm2}	-0.4500
Helix angle of Gear 1 (mean) β_{m1}	35°	Tooth thickness modification coefficient X_{m1}	0.0364
Addendum angle of Gear 2 θ_{z2}	1.9246°	Tooth thickness modification coefficient X_{m2}	-0.0550
Dedendum angle of Gear 2 θ_{fz}	5.0740°	Mass of Gear 1（ISO 17485） Q_{m1}	6
Face width of Gear 1	5mm	Mass of Gear 2（ISO 17485） Q_{m2}	8
Face width of Gear 2	5mm	Shaft angle Σ	90°

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The tooth-profile modeling shown in Fig. 5 is carried out in accordance with the ISO 23509 standard [14]. Multiple characteristic sections are selected along the tooth-width direction, and involute tooth profiles arranged at 90° are established in the virtual cylindrical gear plane. The gear flank is then generated by sweeping these sections. The tooth profile of each section is angularly transformed according to its spatial position, and the section posture during the face-milling process is calculated using auxiliary angles. The tooth surface formed along the tooth-width direction can thus be approximately described as an extended epicycloid or a circular-arc tooth profile.

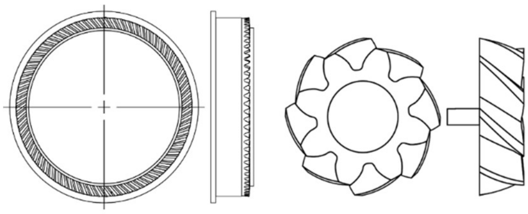

Fig. 5 Three-Dimensional Schematic Diagram of the Hypoid Gear

3.3 Working Principle and Structural Design of the Hollow-Shaft Outer-Rotor Generator

The hollow-shaft outer-rotor generator designed in this study is mainly developed based on magnetic-circuit parameters and electrical parameters. The magnetic-circuit parameters include remanence, magnetomotive force, and magnetic loading, while the electrical parameters include electric loading, output voltage, and output current. As shown in Fig. 6, the generator is mainly composed of the guide-vane-side armature and stator winding, and the turbine-side permanent magnet poles. During operation, the drilling fluid is rectified by the guide vane and then acts on the turbine blades, driving the turbine and the outer-rotor magnetic poles to rotate. As a result, relative motion is generated between the rotating magnetic field and the stator winding, inducing an electromotive force and realizing the conversion of hydraulic energy from the drilling fluid into electrical energy.

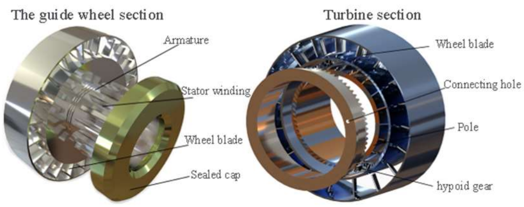

Fig. 6 Schematic Diagram of the Outer-Rotor Generator

At present, the generator types commonly used in downhole turbine power generation systems mainly include permanent magnet synchronous generators, capacitor-excited asynchronous generators, and brushless synchronous generators. Among them, permanent magnet synchronous generators have the advantages of simple structure, high power density, compact size, and good low-speed power generation performance, making them more suitable for low-power and compact downhole hydraulic power generation applications. During generator operation, the mechanical power P_1 obtained by the input shaft is converted into electromagnetic power P_e through electromagnetic induction between the rotating magnetic field and the stator winding after deducting the mechanical loss P_Ω and stator iron loss P_{Fe}. The corresponding power balance relationship can be expressed as follows:

$$P_1 = P_\Omega + P_{Fe} + P_e \tag{3}$$

$$P_e = P_{cua} + P_2 \tag{4}$$

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Where, $P_{cua}=mI^2R_a$; $P_2=mUI\cos\varphi$; $m$denotes the number of stator phases

Dividing both sides of the power equation by the synchronous angular velocity ω, the torque equation can be obtained as follows:

$$T_1 = T_0 + T_e \tag{5}$$

where $T_1$is the driving torque of the prime mover: $T_1=P_1/\omega$;$T_e=P_e/(\omega T_e)$;$T_e=P_e/\omega$;T_0 denotes the no-load torque of the generator: $T_0=(P_\Omega+P_{Fe})$.

Meanwhile, the power factor of the outer-rotor generator needs to be calculated, and the fundamental phase angles of the voltage and current, namely Phi_V and Phi_I, are obtained. If abs (Phi_V) > abs (Phi_I), a leading power factor is obtained; if abs (Phi_V) < abs (Phi_I), a lagging power factor is obtained:

$$cos(Phi) = cos(abs(Phi_V - Phi_I)) \tag{6}$$

When the sinusoidal current is zero, the total harmonic distortion is denoted as THD_{2i}; when the sinusoidal voltage is zero, the total harmonic distortion is denoted as THD_{2U}. The total harmonic distortion THD is expressed using the total harmonic distortion ratio:

$$PF = \frac{cos(Phi)}{\sqrt{(1 + THD_{2i}^2)(1 + THD_{2u}^2)}}$$

The axially segmented rotor structure helps reduce eddy current losses and local heating, thereby improving the operating efficiency of the generator. The air-gap size is generally determined by the stator inner diameter and the air-gap width, and can also be characterized by the radial dimensional relationship between the stator inner diameter and the rotor outer diameter. Based on the above principles, a hollow-shaft outer-rotor generator model is established, as shown in Fig. 7, which presents the winding arrangement, axial structure, and radial cross-section schematic.

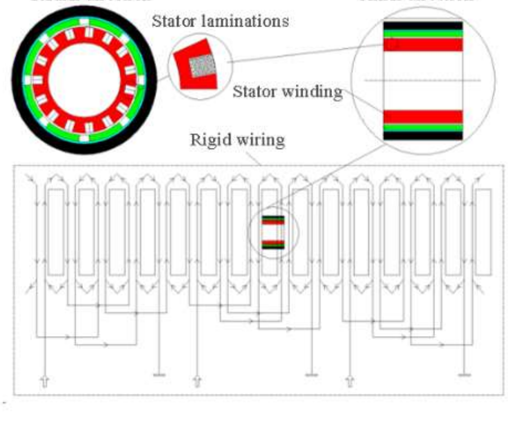

Fig. 7 Outer-Rotor Generator Model

The driving torque of the downhole turbine generator is provided by the output torque of the turbine mechanism, and the turbine output power directly determines the power matching and output

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capability of the generator. Therefore, the output characteristics of the turbine and the electromagnetic parameters of the generator need to be designed cooperatively. The main design parameters of the hollow-shaft outer-rotor permanent magnet generator are listed in Table 3.

Table 3. Parameters of the Hollow-Shaft Outer-Rotor Permanent Magnet Generator

Rotor parameters	Value	Stator parameters	Value
Number of poles	8	Number of slots	15
Core yoke thickness	1mm	Armature diameter	50mm
Permanent magnet arc length	140mm	Slot width	4mm
Number of permanent magnets	1	Slot depth	5mm
Number of phases	3	Slot opening	3
Slot insulation thickness	0.25mm	Air gap	1mm
Conductor spacing	0.1mm	Central shaft-hole diameter	35mm

3.4 Modeling and Assembly of the Downhole Variable-Angle Hollow-Shaft Turbine Generator

From the perspective of structural design, the turbine generator in this study is configured with a hollow shaft so as to reserve a central passage for the penetration and deployment of other downhole tools while satisfying power generation requirements. The installation angle of the turbine blades is adjusted through a hypoid gear mechanism to ensure stable power generation under different flow-rate conditions and to avoid interference with other downhole operations. In the overall system layout, the hollow-shaft outer-rotor generator is integrated into the variable-angle turbine structure, with a guide vane arranged at the inlet to improve the incoming flow conditions, while the hypoid gear mechanism is used to realize the transmission for blade angle adjustment. The principal difference between the variable-angle turbine and a conventional fixed-blade turbine lies in the adjustability of the blade setting angle. By changing the blade angle, the blade throat area can be adjusted, thereby altering the turbine flow capacity, enabling active adaptation to different flow-rate operating conditions, and improving the turbine operating efficiency. A dynamic seal is adopted between the guide vane and the turbine, and the hypoid gear rotates synchronously with the turbine. When adjustment of the blade attack angle is required, the gear mechanism can be driven manually or automatically to rotate all blades synchronously. If automatic adjustment is employed, an automatic control actuator connected to the guide vane can be further configured to realize online adjustment of the blade attack angle. The overall assembly is shown in Fig. 8.

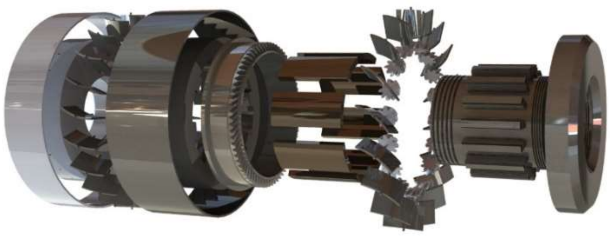

Fig. 8 Exploded View of the Downhole Variable-Angle Hollow-Shaft Turbine Generator

4. Conclusion

To address the insufficient wide-flow-rate adaptability, limited structural integration, and occupation of the central passage for downhole tools in existing downhole turbine power generation systems, this study proposes a downhole variable-angle hollow-shaft turbine power generation system. The key structural designs of the guide vane, variable-angle turbine, hypoid gear adjustment mechanism, and hollow-shaft outer-rotor permanent magnet generator are completed. With the variable-angle turbine as the core component and the hollow-shaft outer-rotor permanent magnet generator as the energy conversion unit, the system can realize continuous conversion among drilling-fluid hydraulic energy, turbine mechanical energy, and electrical energy. Meanwhile, the hollow-shaft configuration reserves a central passage for the penetration of other downhole tools. In the design, the guide vane is equipped with 15 guide blades, and the blade inlet angle is set to $\alpha=0°$. The turbine is designed with a mass flow rate of 45 kg/s, a specific speed of 55, 10 blades, an isentropic efficiency of 72.5%, and an outlet velocity coefficient of 96%. Fourteen turbine models with different blade attack angles ranging from 0° to 90° are established to analyze the influence of blade setting angle variation on flow capacity, flow distribution, and hydraulic efficiency. Meanwhile, a hypoid gear adjustment mechanism with a transmission ratio of 8.87 and a design life of 20,000 h is designed to realize synchronous angle adjustment of multiple blades. An 8-pole, 15-slot, three-phase hollow-shaft outer-rotor permanent magnet generator is constructed, with a central shaft-hole diameter of 35 mm, enabling compact power generation while ensuring the continuity of the central passage. The results establish a structural design method for a downhole variable-angle hollow-shaft turbine power generation system suitable for wide-flow-rate operating conditions, providing a reference for the structural optimization, performance analysis, and engineering application of downhole turbine power generation devices.

References

[1] Li, T. H. (2020). *Study on aerodynamic performance of turbine sector cascades with adjustable geometry* [Doctoral dissertation]. Harbin Institute of Technology.

[2] Lu, H. P. (2017). *Research on parameter matching and structural optimization of generator drive wheel and turbine in underground environment* [Doctoral dissertation]. Southwest Petroleum University.

[3] Zhang, Y. K. (2021). *Research on variable geometry turbine design technology* [Doctoral dissertation]. Nanjing University of Aeronautics and Astronautics.

[4] Gabriel, B., Diego, B., René, G., et al. (2022). Physics-based observers for measurement-while-drilling system in down-the-hole drills. *Mathematics*, 10(24), 4814. https://doi.org/10.3390/math10244814

[5] Li, F., Zhao, J. C., Lu, J. F., et al. (2022). Modeling and output characteristics analysis of drilling-while-generating permanent magnet turbine generator. *Instrumentation Technology*, (3), 55–59.

[6] Ji, L., Zhang, G. Q., Liu, J. Y., et al. (2023). Design and performance testing of generator turbine for rotating directional drilling wells. *Modern Manufacturing Technology and Equipment*, 59(3), 15–18.

[7] Rakshith, S., Joseph, S., & Michael, M. (2023). Development of annular pump to enhance drilling distance and cuttings return in horizontal directional drilling. *Tunnelling and Underground Space Technology incorporating Trenchless Technology Research*, 140. https://doi.org/10.1016/j.tust.2023.105302

[8] Sun, J. (2024). *Design and optimization of underground turbine generator blades based on blade load distribution* [Doctoral dissertation]. Lanzhou University of Technology.

[9] Jia, C. (2023). *Optimization and analysis of the turbine guide wheel structure of underground turbine generators* [Doctoral dissertation]. Xi'an Petroleum University.

[10] Kanimozhi, B., Prakash, J., Pranesh, V. R., et al. (2019). Numerical and experimental investigation on the effect of retrograde vaporization on fines migration and drift in porous oil reservoir: roles of phase change heat transfer and saturation. *Journal of Petroleum Exploration and Production Technology*, 9(4), 2953–2963. https://doi.org/10.1007/s13202-019-00775-9

[11] Sam, A. A., Mondal, J., & Ghosh, P. (2017). Effect of rotation on the flow behaviour in a high-speed cryogenic microturbine used in helium applications. *International Journal of Refrigeration*, 81, 111–122. https://doi.org/10.1016/j.ijrefrig.2017.05.016

[12] Juha, P., Tapani, J., & Valéria, H. (2008). *Design of rotating electrical machines*. John Wiley & Sons, Ltd.

[13] Liu, S. Y. (2021). *Research on geometric design and intermeshing characteristics of small intersecting-angle quasi-hyperbolic surface gear transmission* [Doctoral dissertation]. Chongqing University.

[14] Han, Z. H., Shi, W. K., Xu, L., et al. (2017). Geometric and mating characteristics changes of tooth profiles and mating characteristics of composite cycloidal low-difference planetary transmission. *Engineering Science and Technology*, 49(6), 171–183.