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Research on Multi-Stage Optimization of Impeller For Multi-stage Culvert Type Natural Gas Pressure Energy Power Generation Device

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ABSTRACT

Under the "dual carbon" framework, the pressure energy benefit of recovering natural gas pressure regulation loss is significant. This article proposes an optimized design for a multi-stage culvert impeller, featuring a relatively simple structure, small footprint, and low leakage risk, specifically tailored for existing pressure difference power generation technology. Through optimization of the number of stages and spacing, it is confirmed that the theoretical power of a three-stage impeller increases by 31.8% compared to a single-stage impeller under a spacing of twice the impeller radius, providing an efficient and low-leakage solution for small and medium-sized pressure energy recovery.

KEYWORDS

Pressure Difference Power Generation; Multistage Impeller; Series Optimization; Spacing Optimization.

1. INTRODUCTION

In line with the increase in the world population, natural gas, which has an increasing share in fossil fuels[1]. As more and more attention has been paid to environmental problems, natural gas is increasingly used [2]. By 2023, the consumption of natural gas had grown to 394.53 billion cubic meters [3]. The total mileage of long-distance pipelines in China reached 124,000 kilometers in 2023 [4]. However, high-pressure natural gas releases tremendous energy during the process of pressure reduction [5]. Establishing an energy structure that is energy-saving, efficient, clean and low-carbon will be an inevitable trend in energy development [6]. Recycling and utilizing its pressure energy can enhance economic and environmental benefits [7]. However, the external expansion machine equipment requires a large space, and due to the presence of couplings, the risk factor increases [8].

To this end, this paper innovatively presents a multi-stage ducted natural gas pressure energy power generation device, which improves energy capture efficiency through the collaborative work of multi-stage impeller groups. In the selection of key components, since the radial-flow impeller may generate considerable noise [9], while the axial-flow impeller has a smaller impact on the fluid flow direction, relies on pressure difference to drive rotation and has a high energy conversion efficiency, it was determined to adopt the axial-flow impeller [10]. At the same time, active magnetic levitation bearings were chosen instead of traditional mechanical bearings, whose vibration suppression characteristics can effectively isolate mechanical vibration, eliminate friction loss and leakage risk, and improve energy conversion efficiency [11]. In addition, the multi-segment housing design takes into account the convenience of installation and maintenance.

In terms of the design and optimization of the impeller, the airfoil is the foundation for the modeling of the moving blades [12]. This paper follows the "airfoil - blade - impeller" system design process. Based on the NACA0012 airfoil, five new airfoils were derived. Through simulation, the airfoil with a downward angle of 12° was determined to be the optimal one. Its key aerodynamic performance is significantly superior to that of the original airfoil, so it was selected as the base airfoil. Based on airfoil optimization and the Wilson method, 3/4/5-blade impeller models were designed. At different flow rates, there is a pressure drop in the inlet area of the moving impeller [13]. Further simulation results show that the 5-blade impeller exhibits the maximum theoretical energy gain coefficient of 0.42 and the highest theoretical power of 2.45 kW when the tip speed ratio is 4. These research results provide solid and powerful theoretical support and practical basis for the subsequent design of multi-stage impellers.

2. DESIGN OF MULTI-STAGE IMPELLER

To optimize the energy capture efficiency of multi-stage impellers, this study established a fluid motion simulation model using the ANSYS Fluent platform. The dynamic mesh model (DG) was combined with the standard k-ε turbulence model to balance calculation accuracy and efficiency. Given the characteristics of high-pressure and low-speed flow of natural gas, the poly-hexcore hybrid grid is adopted to enhance efficiency. The interface between the rotating domain and the outer domain is locally densified to 4mm for grid division. The simulation conditions are set as follows: velocity inlet at 50m/s, pressure outlet at 0.1MPa, pressure-based transient solver, time step at 0.005s, 1000 time steps, and the maximum number of iterations per time step is set to 30. Based on this model, the system conducts a comprehensive study on the collaborative influence of the number of impeller stages and the spacing on the efficiency of pressure energy capture.

2.1. Discussion on The Number of Impeller Stages

The number of impeller stages is a key parameter that affects the energy capture efficiency of this power generation device. To study the effect of the number of impeller stages on energy acquisition, two-stage and three-stage impellers were added as controls on the designed impellers. Fig. 1 shows the three-dimensional model.

(a) Secondary Impeller (b) Tertiary Impeller

Figure 1. Multi-stage Impeller Model

Since the current study mainly focuses on the influence of the number of impeller stages on the energy conversion efficiency, to avoid the influence of the wake flow, the spacing between each stage of the impellers is set to be one times the radius of the impeller. This spacing study will be left for future work.

To analyze the effect of the number of impeller stages on the performance of the impeller under different flow rate conditions, Fluent software was used to conduct simulation analysis on the impeller groups with three types of impeller stages. In this paper, three stages of impellers with velocity inlets of 40m/s, 45m/s, and 50m/s were selected as examples. The aerodynamic performance of each stage of impellers was analyzed by observing the velocity cloud and pressure cloud.

The research found that at low flow rates, the pressure differences at each stage of the impellers were similar and positively correlated with the flow rate. When the flow rate was 31-36 m/s, the pressure difference of the first stage of the impeller was higher than that of the second stage, resulting in better performance; when the flow rate was 35-40 m/s, the pressure difference of the second stage increased more rapidly, leading to better performance. Comparing the second and third stages of the impellers, it was found that the pressure difference of the second stage was higher at 38-42 m/s; at other flow rates, the pressure difference of the third stage was larger, and it increased more rapidly in the high-speed stage. Within the range of 30-50 m/s, the pressure difference of the third stage was always greater than that of the first stage and increased more rapidly. In conclusion, the energy capture performance of the third-stage impeller was the best, followed by the second stage, and the first stage was the lowest.

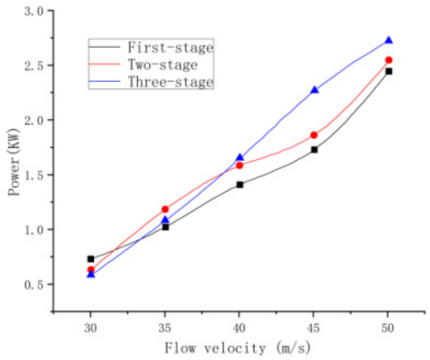
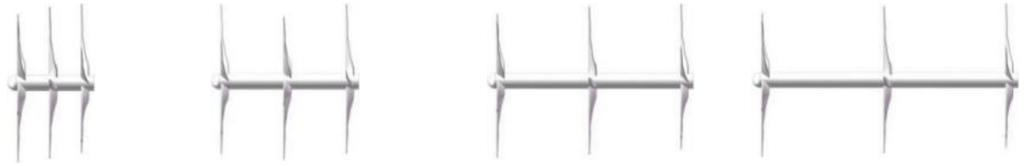


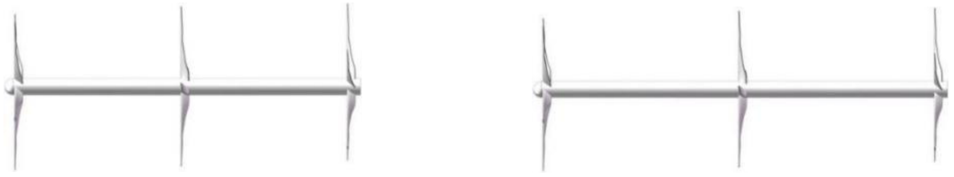
Figure 2. Power Curve of the Multi-stage Impeller

Fig. 2 shows the theoretical power curves of the first, second and third stage impellers when the natural gas flow rate is 30m/s-50m/s, from which it can be seen that: the power of the three types of series impeller varies with the inlet flow velocity: at low flow rates, the first stage is the best; at 30-31.5 m/s, the second stage is lower than the first stage due to the drag effect; at 30-34 m/s, the third stage is significantly lower than the first stage due to the higher drag effect of multiple stages and has a later overspeed point; at 30-38 m/s, the second stage has a higher power at the end of the third stage due to the drag effect, and after exceeding 38 m/s, the third stage overcomes it due to the synergy of multiple stages and becomes the best at high flow rates.

2.2. Discussion on Impeller Spacing



(a) 0.4 Times R (b) 0.8 Times R (c) 1.2 Times R (d) 1.6 Times R



(e) 2 Times R (f) 2.4 Times R

Figure 3. Impeller Models with Different Spacings

After the fluid flows through the upper-stage impeller, it will generate a wake. The lower-stage impeller operating in the wake environment will result in a decrease in energy capture efficiency. In severe cases, a "dragging" effect will occur. Therefore, the impeller spacing needs to be optimized to avoid interference, thereby improving the energy conversion efficiency.

In the design of multi-stage impellers, the radius R of the impeller is generally used as the variable unit, and six different impeller spacings are set: 0.4R, 0.8R, 1.2R, 1.6R, 2R, 2.4R. Fig. 3 shows the impeller models of the above six different impeller spacings.

Through CFD simulation analysis, the flow field characteristics of six types of impellers were studied. The torque coefficient, energy capture coefficient and thrust coefficient of each impeller were calculated. The influence law of spacing on energy capture efficiency was evaluated.

The research found that when the impeller spacing increased from 0.4R to 0.8R, the performance coefficient decreased: when the spacing was too small (0.4R), the impeller group was approximately a single unit, and the energy exchange was too strong; after the spacing increased to 0.8R, due to the insufficient energy recovery of the first-stage impeller, the subsequent energy gain was limited. When the spacing continued to increase, the airflow had sufficient recovery space, and the performance coefficient increased accordingly. However, when the spacing reached 2.4R, due to the intensified energy loss between the stages and the deterioration of the incoming flow conditions, the performance coefficient decreased again, resulting in a reduction in the overall energy gain efficiency.

Furthermore, the impeller spacing is negatively correlated with the thrust coefficient. This indicates that an increase in spacing can reduce the axial thrust and enhance the stability of the device. Based on the calculated impeller torque and rotational speed obtained from the simulation, the theoretical power of the impeller was calculated as shown in Fig. 4.

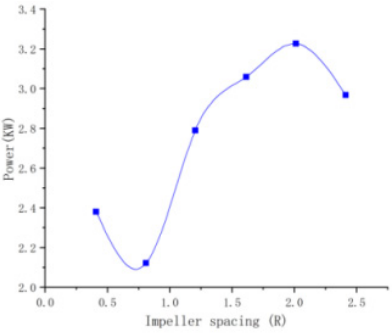
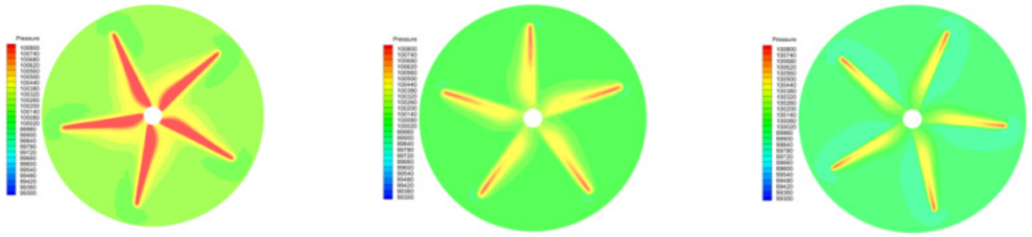


Figure 4. Power of Impellers at Different Spacings

As can be seen from the figure, the theoretical power of the 0.8R spacing impeller is the lowest (2.12 kW), while that of the 2R spacing impeller is the highest (3.23 kW), with a difference of 52.3%. Therefore, based on the above analysis, the 2R spacing three-stage impeller with the best overall performance is selected as the final impeller for the device.

3. VALIDATION OF MULTI-STAGE IMPELLER PERFORMANCE



(a) 5mm in front of the first stage impeller

(b) 5mm in front of the secondary impeller

(c) 5mm in front of the final-stage impeller

Figure 5. Pressure distribution at different radial sections of the impeller

To verify the performance of the multi-stage impeller, the energy capture situation of each impeller was analyzed step by step. When the natural gas flows through the impeller, the blades block and form a high-pressure area (the pressure gradient on the upstream surface matches the shape of the blades). The pressure on the downstream surface drops sharply and then gradually recovers as the natural gas continues to flow. This indicates that the energy of the natural gas is also gradually recovering.

Compared with the pressure cloud of the 5mm section in front of the third stage impeller, as shown in Fig. 5, the first-stage's red high-pressure area almost covers the entire blade (large surrounding yellow zone); the second-stage's red area is smaller (middle-to-tip), and the third-stage's is similar to the second-stage (only a small tip area). Table 1 lists the average pressure difference of the 5mm sections before and after each stage.

Table 1. Average Pressure Difference of 5mm Cross-sectional Surface Before and After Each Impeller

Impeller stages	Head stage	Secondary	The final level
Average face pressure difference (Pa)	957	421	124

From the table, it can be seen that the first-stage impeller captures the most pressure energy (with an average pressure difference of 957 Pa), while by the second stage, it is less than half of that of the first stage, and at the last stage, it is only 124 Pa. This indicates that the impeller has already captured most of the pressure energy. Further increasing the Impeller stages will have limited effect on improving energy efficiency, and it may even have a dragging effect on the preceding impellers, negatively impacting the energy capture efficiency of the impellers.

4. SUMMARY

This study is the first to apply multi-stage impellers to the recovery of gas pressure energy. Through series optimization (three-stage impellers) and spacing optimization (2R), the power was increased by 31.8% compared to a single-stage impeller, providing an efficient and low-leakage solution for small and medium-sized pressure energy recovery.

Performance verification: The capturing ability of a three-stage impeller with a wheel spacing of 2 times R was analyzed. The transition between each stage of the impeller was smooth, and the average pressure difference on the final impeller surface was reduced to 124 Pa, indicating that most of the gas pressure energy had been captured by the impellers.

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