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EFFECT OF BOWED STATOR ON AERODYNAMIC PERFORMANCE AND STRUCTURAL STRENGTH OF A HIGH-LOADED TURBINE FOR CAES SYSTEM

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ABSTRACT

The efficiency of high-loaded axial turbines significantly influences the performance of Compressed Air Energy Storage (CAES) system. In present study, the effect of bowed stator on aerodynamic performance of a turbine is investigated by further considering structural strength of rotor. A fluid-structure interaction model is thus proposed, and the variation of isentropic efficiency, mass flow rate, stress and deformation of rotor with bowed parameters of stator are revealed. The bowed stator with bowed angle of 15° and normalized bowed height of 0.3 are suitable in present study, which also increases the isentropic efficiency at variable operation condition without influencing the stress significantly. The obtained results can provide a useful guide for design, optimization and application of the turbine in CAES system.

Keywords: compressed air energy storage, turbine, bowed stator, fluid-structure interaction, CFD

NONMENCLATURE

Abbreviations	
CAES	Compressed Air Energy Storage
Symbols	
η_{tt}	Isentropic Efficiency
π_{tt}	Total Pressure Ratio

1. INTRODUCTION

Compressed air energy storage (CAES) system is a significant technology for achieving peak power regulation and overcoming the instability of wind and solar energy. These advantages made the system is widely adopted in modern grids [1], renewable energy [2], waste heat utilization [3], and other fields [4].

Axial turbine is a significant power output device in CAES system which significantly influences the performance of CAES system. The axial turbines adopted in CAES system always operated at the condition with higher total pressure and lower temperature. As a result, stator with lower aspect ratio is adopted and secondary flow loss near hub and shroud is increased. To overcome the shortage, bowed stator is adopted and a lot of researches [6]-[9] have been conducted in recent years.

Furthermore, the axial turbine in CAES system also operated under high load condition to obtain more power generation with less system complexity and cost, and more attention is paid on structural strength.

However, the effect of bowed stator on both of aerodynamic performance and structural strength is still not revealed completely. In present study, effect of bowed stator on a CAES turbine is investigated by adopting fluid-structure interaction analysis. Optimal bowed stator for both of aerodynamic performance and structural strength is proposed. The effect of optimal bowed stator under variable operation condition is also revealed in present study.

2. RESEARCH METHOD

2.1 Method of Fluid-structural Interaction

Sketch for the fluid-structural interaction analysis in present study is depicted in Fig. 1. The Isentropic efficiency and mass Flow rate of the turbine is obtained by CFD model and stress and the deformation of the rotor is solved by FEA (Fimite element analysis) model.

The aerodynamic load solved by CFD model is also transferred to FEA model to obtain the stress and deformation of rotor by considering effect of bowed stator.

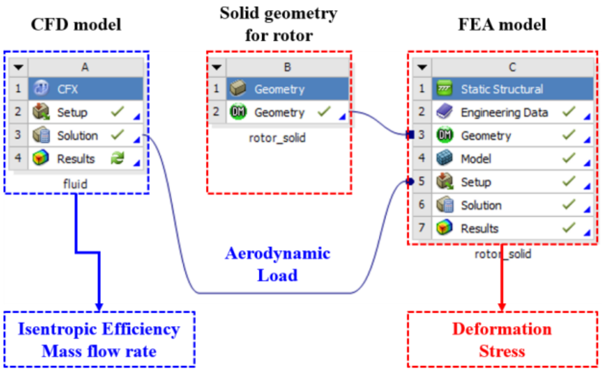


Fig. 1 Sketch for the fluid-structural interaction analysis in present study

2.2 Models for Fluid-structural Interaction analysis

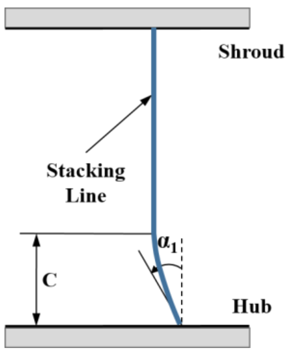


Fig. 2 Bowed parameters for stator in present study

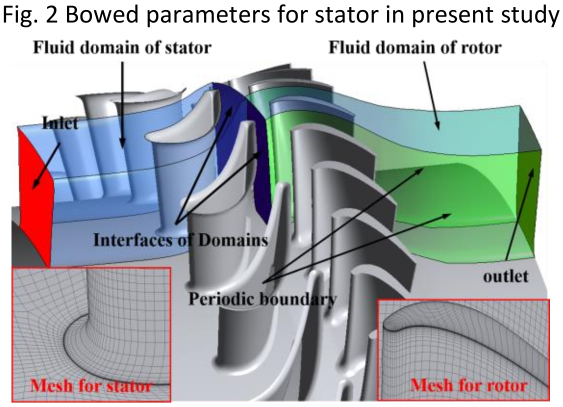


Fig. 3 CFD model of the turbine in present study

"L" type bowed stator is selected and adopted in preset study. The CFD model is proposed in Fig. 2, which including Single flow passage domain, rotational periodicity and "stage" domain interface. Around 701056 elements are adopted in CFD model. The FEA model of the rotor is provided in Fig. 4, which including a displacement constraint, circumferential displacement constraint, and aerodynamic load solved by CFD code and applied on the blade surface. Around 225504 tetrahedral elements is adopted in the FEA model.

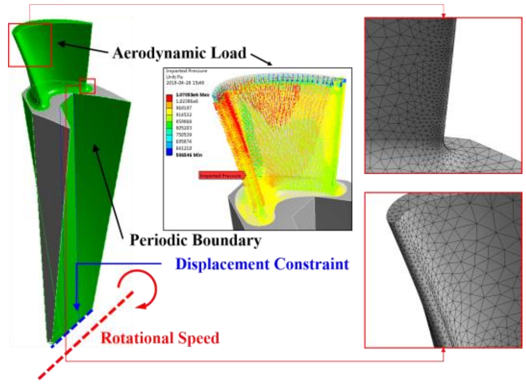


Fig. 4 FEA model of the turbine in present study

3. RESULTS

3.1 Effect of bowed parameters of stator on turbine

The variation of isentropic efficiency with bowed angle is influenced by normalized bowed height. As shown in Fig. 5, the isentropic efficiency increased as bowed angle increased when normalized bowed height is 0.3 while the isentropic efficiency is decreased when normalized bowed height is 0.5 and 0.7.

However, the mass flow rate increased as bowed angle of stator increased (Fig. 6), which increased more obviously at higher normalized bowed height.

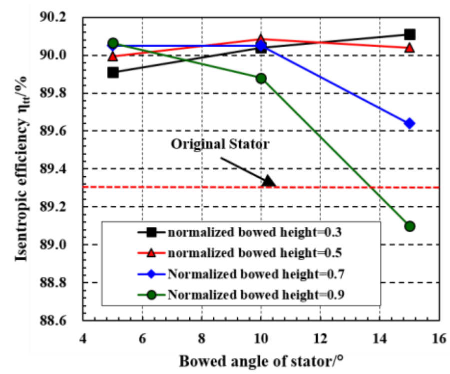


Fig. 5 Effect of bowed parameters on isentropic efficiency

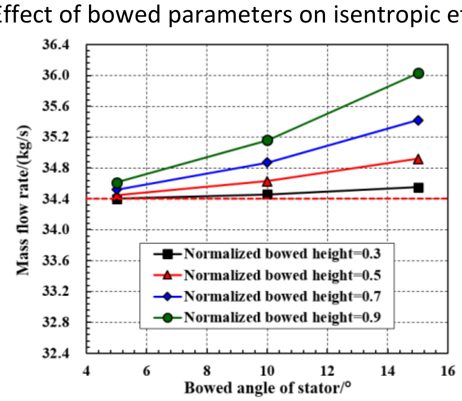


Fig. 6 Effect of bowed parameters stator on mass flow rate

Both of the Maximum Von-Mises stress (Fig. 7) and total deformation (Fig. 8) also increased with the increase of bowed angle, and much more obvious increment can also be found for higher normalized bowed height.

Based on the results above, It can be found that bowed angle=15° and normalized bowed height=0.3 are optimal for the bowed stator in present study. As shown in Fig. 9, the flow loss caused by tip leakage flow, upper and lower passage vortex can be suppressed effectively although the flow loss near hub is increased.

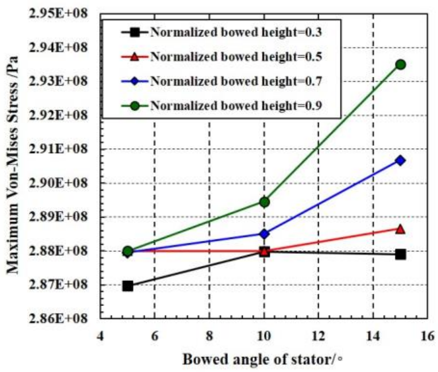


Fig. 7 Effect of bowed parameters on stress of rotor

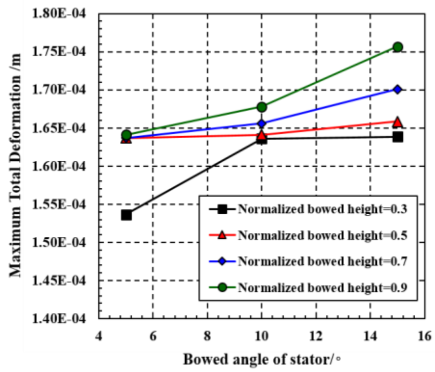


Fig. 8 Effect of bowed parameters on deformation of rotor

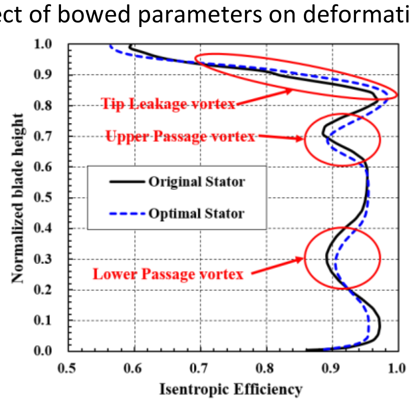


Fig. 9 Effect of bowed stator with optimal parameters on span wise distribution of efficiency

3.2 Effect of bowed stator under variable operation condition of CAES system

The optimal bowed stator also presents higher isentropic efficiency at different total pressure ratio (Fig. 10). The flow loss in the passage is obviously suppressed by the optimal bowed stator when π_{tt} is 2.71 and 1.92 respectively (Fig. 10). The flow loss caused by negative attack angle is also suppressed by optimal bowed stator when total pressure ratio π_{tt} is decreased to 1.17.

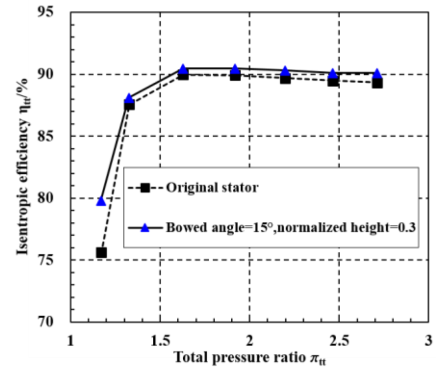
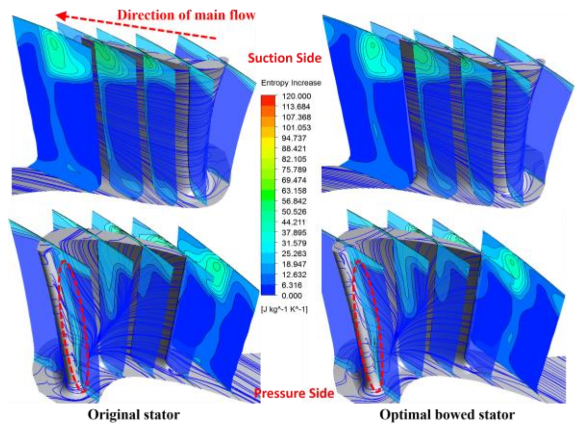
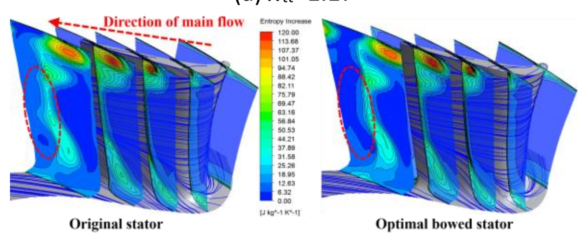


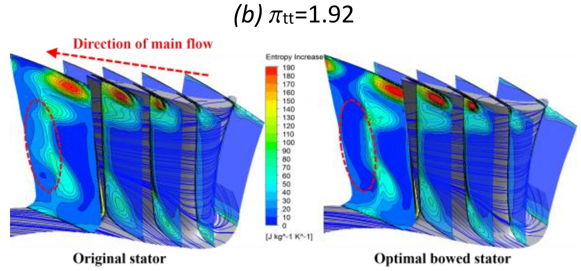
Fig. 10 Variation of η_{tt} with total pressure ratio



(a) π_{tt}=1.17



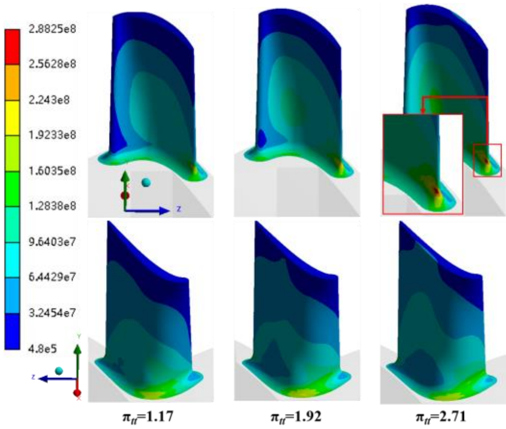
(b) π_{tt}=1.92



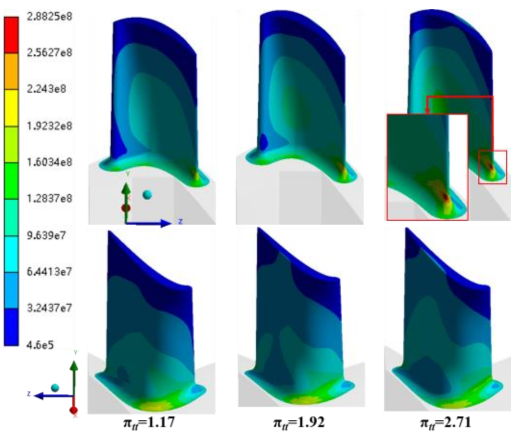
(c) π_{tt}=2.71

Fig. 11 Entropy increase in the rotor at different total pressure ratios

Same variation of stress with total pressure ratio can be found for original stator and optimal bowed stator, and a region with maximum stress is observed at trailing edge of blade near hub. With the increase of total pressure ratio, the Von-Mises stress is increased.



(a) Original stator



(b) Optimal bowed stator

Fig. 12 Stress distribution at blade of rotor at different total pressure ratios

3.3 Conclusions

The corresponding conclusion can be drawn as follows:

(1) The isentropic efficiency increased as bowed angle of stator increased when normalized bowed height is 0.3. However, the isentropic efficiency decreased as bowed angle of stator increased when normalized bowed height is 0.7 and 0.5. The mass flow rate increased as bowed angle of stator increased. And the increment becomes more obviously at higher normalized bowed height.

(2) The variation of structural strength with bowed parameters is firstly provided in present study. Both of the Maximum Von-Mises stress and total deformation increased with the increase of bowed angle, and much more obvious increment is observed when normalized bowed height are 0.5, 0.7 and 0.9 respectively.

(3) The optimal bowed angle and normalized bowed height is 15 ° and 0.3 respectively, which can increase the isentropic efficiency by 0.8% without obviously increasing mass flow rate. The optimal bowed stator also increases the isentropic efficiency at each total pressure ratio, and the stress is not influenced significantly.

ACKNOWLEDGEMENT

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