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Research Paper

Effects of rotor solidity and leakage flow on the unsteady flow in axial turbine

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HIGHLIGHTS

- The solidity effects on the unsteady flow both in full and partial admission turbines are revealed.
- The combined effects of leakage flow and partial admission flow are presented.
- The frequency excitation amplitude can be modified via solidity.
- Leakage flow is beneficial to the axial aerodynamic exciting force reduction.

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ABSTRACT

Partial admission turbine plays an important role in power control, which strengthens the unsteady flow. The effects of rotor solidity at partial admission condition can be more complicated, and leakage flow deeply strengthens the unsteadiness. Hence, the investigations of rotor solidity and leakage flow on the unsteady flow are of great significance for turbine designs. Turbines including five kinds of solidity at full and partial admissions are modeled based on 3D viscous compressible NS equation. In addition, the leakage flow model including tip leakage, inlet and outlet cavity is investigated. The results show that the solidity effects on partial admission turbine are not exactly the same as that on full admission turbine. The differences are identified, especially the axial unsteady aerodynamic force. Moreover, the attack angle tends to be negative with rotor solidity increasing; meanwhile, the low pressure region varies with solidity due to flow separation or throat area reduction. Leakage flow model is more able to reveal the unsteady flow, and the comparative analysis of flow phenomenon under the combined effects of leakage flow and partial admission flow is conducted. The change of rotor inlet parameters is smoothed down for leakage model and the axial exciting force is relative lower.

1. Introduction

The output power is usually adjusted by three ways including sliding pressure, throat value and partial admission to meet the requirement of external load. The sliding pressure operation adjusts loads through the boiler. Hence, it takes a long time to cope with changes. The mass flow can also be controlled with throat value while the efficiency is relatively lower due to large pressure losses and short blades. Partial admission method can meet the load change through the intake area adjustment. Further, it is widely used due to no throttling loss, low secondary losses and the rapid load response. However, the unsteady flow in turbine is extremely complicated and then the partial admission construction strengthens the unsteadiness. Compared to full admission turbines, windage loss and arc end loss are induced at the partial admission turbine as well as unsteady low frequency excitation of aerodynamic forces. In order to realize higher efficiency and reliability, the investigations of partial admission are of a great significance to the industry.

Nowadays, the deep researches on the unsteady flow in partial admission turbines have been carried out. The performance of partial admission turbines with impulse design has been discussed by Ohlsson [1] through theoretical method based on incompressibility and non-friction assumption. The detailed flow parameter distributions of the partial admission control stage have been presented by He [2] through 2D unsteady numerical method. It also points out that the mixing process may benefit the turbine overall performance. Hushmandi [3] indicates that 3D influence on the turbine unsteady flow is very important based on two low reaction stages

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Nomenclature

$C_{3\varepsilon}$	variables which determines how dissipation rate affected by the buoyancy, [–]
M_t	turbulent Mach number, [–]
k	kinetic energy of turbulence, [kJ]
T	torque, [N∗m]
c_2	absolute velocity at rotor outlet, [m∗s^{-1}]
w_2	relative velocity at rotor outlet, [m∗s^{-1}]
n	rotation speed, [r∗min^{-1}]
$C_{ax,rotor}$	axial chord of rotor
F_{AT}	tangential force of all blades
a_m	exponent coefficient
m	exciting order
$C_{ax,blade}$	axial chord of blade
F_{AA}	axial force of all blades
w_1	relative velocity at rotor inlet, [m∗s^{-1}]
Δh^{ast}	ideal enthalpy drop
c_1	absolute velocity at rotor inlet, [m∗s^{-1}]
u	velocity components in a generalized coordinate system, [m∗s^{-1}]
C_μ	modified constant, [–]
$\dot{m}$	mass, [kg]
G_b	generation of turbulence due to buoyancy, [–]

Greek

α_k	inverse effective Prandtl numbers, [–]
ρ	density, [kg∗m^{-3}]
ε	dissipation rate, [–]
μ_{eff}	effective dynamic viscosity coefficient, [Pa∗s]
β	coefficient of thermal expansion, [–]
α_1	absolute flow angle at rotor inlet, [deg]
α_2	absolute flow angle at rotor outlet, [deg]
β_1	relative flow angle at rotor inlet, [deg]
β_2	relative flow angle at rotor outlet, [deg]
η	efficiency
ζ	degree of admission

model. Unsteady flow and exciting force under four partial admission degrees are in detailed comparison based on 3D unsteady numerical investigation by Xie [4]. Bohn [5] and Fridh [6] conduct experimental investigations on the unsteady flow in turbines. The flow parameters non-uniformity caused by partial admission is also pointed out. Tousi [7] shows that the turbine efficiency is closely related to partial admission degree. And the optimum partial admission degree is obtained through numerical analyze. The flow parameters of the partial admission turbine at rated and off-designed conditions are investigated by Song [8]. In addition, the partial admission turbine used in ORC are analyzed by Cho [9] and Martins [10].

Although the investigations on partial admission are very extensive, only a few studies focus on the effect of rotor solidity on turbine performance. The solidity plays an important role in blade design. As far back as 1945, Zweifel [11] has estimated optimum solidity for turbines with large angular deflection. However, Horlock [12] and Aungier [13] points out the Zweifel correlation limitation that the prediction of optimum solidity is also limited to the outlet flow angle. In addition, the effects of rotor solidity on the full admission stage efficiency have also been investigated by Simpson [14] and the optimum solidity is approximately 1.25 for the investigated model. Only little information regarding the optimum solidity for axial or radial turbine stages is available, while the important effects of solidity on wind turbine performance have been valued [15,16]. When it comes to the partial admission turbine investigations, the references can be much less. According to the open literature, Cho [17,18] has merely done preliminary research on the effects of rotor solidity on aerodynamic force and the results show that the tangential force of single rotor increases with the reduction of rotor solidity while the axial force decreases.

Meanwhile, limited to the computing resource and the complexity of modeling, the researches of leakage flow effects are mainly focused on the turbine efficiency or heat transfer, which are with steady leakage models or unsteady periodic admission models. The research can be of a great benefit to understand the leakage flow on the turbine aerodynamic performance. The influences of the tip geometry on leakage flows are investigated by Krishnababu [19] through single passage with the periodic boundary. The result shows the leakage mass flow increases with the gap and the hollow structure contributes to the reduction of leakage mass flow. The leakage flow and main flow interaction is studied by Anker [20] based on the numerical method, and it is found that the leakage flow along the pitch direction is not uniform. The tip leakage flow and secondary flow interaction is investigated through the unsteady 1.5 stage axial turbine model with shroud by Peters [21]. Pfau [22] obtains the unsteady flow interaction in the rotor inlet cavity based on experimental method for full admission. The vortex structures in the cavity are illustrated. The effects of inlet boundary condition and the relative motion of case on the tip leakage flow have been presented by Coull [23]. The flow structures under different group are also given. In addition, the tip leakage shapes effects on the aerodynamic performance are also investigated by Nho [24], Lee [25,26] and Silva [27]. Partial admission which plays an import role in the power control strengthens the unsteady effects and induces partial admission losses as well as external unsteady exciting forces. Considering the limited investigated model, it is not clear how the aerodynamic performance and unsteady exciting force change under the combined effects of leakage flow and partial admission flow. However, it is extremely important to obtain the accurate flow details and unsteady exciting forces to guarantee higher efficiency and reliability during the control of power output.

As explained above, it is still not clear how rotor solidity affects partial admission aerodynamic parameters and exciting forces. Furthermore, there is hardly any information to illustrate the effects of leakage flow including tip clearance, inlet and outlet cavity on unsteady flow at partial admission. It is necessary to know how the solidity and leakage flow behave at partial admission in an attempt to obtain higher efficiency and reliability. For these reasons, the paper is divided into two parts. First, the turbine unsteady flow performances with 5 kinds of rotor solidity are obtained to reveal the effects of rotor solidity. Secondly, the leakage model including tip clearance, inlet and outlet cavity is modeled, and then the unsteady effects of leakage flow on the partial admission turbine can be obtained by comparing leakage model performance with the no leakage control stage model performance. According to general understanding, the optimum solidity exists due that the larger solidity will give the flow more guidance while larger viscous losses occur. The paper explains why the optimum solidity exists from the new perspective, and it finds that the solidity effects on partial admission turbines are not totally the same as that on full admission turbines. In addition, the paper presents