Effect of Hub Gap on Expanding Stability of Centrifugal Compressor

Chunyang Li¹, Chunjun Ji¹ and Junyi Fang¹,²
¹ Dalian University of Technology, School of Energy and Power Engineering
² Liaoning Fu An gas turbine Co. Anshan, China

E-mail: 906549286@qq.com

Abstract. In this paper, the possibility of using hub gap ("HG" for short) to suppress gas stall and expand the range of stable working condition of compressor is verified by numerical method. The research shows that when designing flow rate, HG increases, the efficiency and pressure ratio of model level decrease. When there is a large flow, the efficiency and pressure ratio of HG model are higher than those without HG. The larger HG is, the higher the efficiency and pressure ratio is. From the analysis of the expanding stability capacity, the model-level flow margin of small HG and large HG is 5% and 15% higher than that of models without HG, and the comprehensive stall margin is 6.87% and 23.59% higher on average. When operating at unstable working conditions, the action of HG causes the airflow in the high pressure zone to flow into the gap and out of the low pressure zone, which improves the flow distribution in the blade passage and makes the flow field stable. However, when operating near the design condition, the leakage flow and its mixing with the momentum of the mainstream are the main sources of aerodynamic loss. The larger HG is, the greater the pressure loss caused by the leakage flow is. Generally speaking, HG can play the role of compressor expansion stability, but at the cost of efficiency; The bigger HG is, the stronger the role of expanding stability is and the greater the efficiency loss is.

1. Introduction
Centrifugal compressor has a certain range of work, the flow is too large or too small can affect its long-term, stable, safe operation, to production. In order to expand the stable working range of compressors, scholars have adopted a variety of measures, such as air injection to affect fluid flow. Researchers include Spakovszky[1] and Skoeh[2] et al. Spakovszky's experiment shows that when the injection mass flow is 0.5% of the compressor mass flow, the surge margin increases by 25%. Marsan et al.[3] evaluated the possibility of using boundary layer suction technology to delay the surge of centrifugal compressor, and designed a multislot control strategy according to the characteristics of unstable pressure field. Casing treatment is also a mature method of expanding stability, which is widely used. He and Zheng[4] pointed that, casing treatment device can effectively eliminate the rotation instability and stall of the impeller inlet at low speed and suppress the surge of the compression system at medium and high speed. Sun et al.[5] explained the mechanism of expanding stability of casing treatment structure and proved its effectiveness.
In the bend of multi-stage centrifugal compressor, influenced by the turning centrifugal force, the air flow angle changes sharply, and the air flow speed changes greatly along the spanwise. Especially in the hub side, there is usually a low-speed airflow region. This part of low-speed gas is easy to break away from the main stream and move along the flow path, which affects the inlet of the downstream reflux, causing the instability of the compressor flow field and the decrease of efficiency. In this paper, HG is used to suppress gas stall, which is verified by numerical method. From the existing literature, the research of HG is basically based on axial compressor. In the axial compressor, in order to manufacture a variable stator vane, there is inevitably a radial gap between the blade and the endwall. The leakage flow of the gap interferes and mixes with the channel vortex and the boundary layer of the suction surface, which increases the aerodynamic loss. Si et al.\textsuperscript{[6]} showed that the larger the hub clearance is, the greater the total pressure loss is. Although the efficiency decreases with the increase of the clearance, it enlarges the working range of the compressor\textsuperscript{[7]}. Mao et al.\textsuperscript{[8]} pointed the loss near the hub increases due to the leakage flow, and the improvement of stall margin is due to the redistribution of mass flow along the spanwise direction. Proper hub clearance can improve the flow condition near the hub of high load stator\textsuperscript{[9][10]}. Lu and Li\textsuperscript{[11]} studied the influence of HG shape (uniform, expansion and contraction gap) on the flow field, pointed out that the expansion gap can weaken the leakage flow near the leading edge, restrain the leakage vortex, and obtain good aerodynamic performance in the hub area.

The research in this paper has two meanings: first, although there are many researches on HG in axial compressor, the influence of HG on compressor’s overall performance, stability expansion ability and flow field is still to be studied because there is no gap in the blade root of centrifugal compressor’s stationary blade usually; second, if HG can be used to control gas flow instability near the bend, it can be extended to other parts and flow channels with larger bending degree in turbomachinery.

2. Numerical Setup
In this paper, the evaluation of HG expansion stability method is based on the structural form of "impeller + integrated static blade", which ensures the existence of blade structure on the wall with large bending degree. The impeller consists 13 blades, connected with 10 integrated static blades. The speed of impeller is 8129 rpm, outlet diameter is 600 mm. The efficiency and pressure ratio at the design point (7.6kg/s) are 82.82\%, 1.483. HG mesh was created in Numeca software AutoGrid5 module. When meshing the blade, the "Row Wizard" function of the module is used to automatically form the blade with HG and generate a structured grid. Model HG was 0 by default. Four simulation models of different gaps (HG = 0.2mm, 0.5mm, 1mm and 3mm) were established by changing the "Hub Gap", and HG was evenly distributed at the blade root. The impeller grid adopts the topology structure of H&I, and the static blade grid adopts the topology structure of O4H. The grid points distribution of the model is shown in Figure 1. The model and grid with HG (as arrow) are shown in Figure 2.

![Figure 1. The grid points of blades.](image-url)
Figure 2. The geometric model.

Model mesh satisfies the min. Orthogonal Angle >10°, the max. Asp. Ratio <2000, and the max. Exp. Ratio <5. Ji et al. [12] has carried out the independence verification of mesh number. The Fine Turbo module was used to solve the three-dimensional Reynolds Navier-Stokes equations, and the turbulence model was Sparlart-Allmaras. The mixed plane method was used to connect rotor to stator, the mesh was encrypted near the wall, and the thickness of the first wall surface was 0.01mm, which met the requirements of the turbulence model y+ value 1-10.

The working medium is air, which is a viscous, compressible gas. The inlet condition is given the flow direction and total temperature and pressure, the outlet condition is given the mass flow rate, and the wall condition is the adiabatic wall with constant speed. The convergence criterion is global residuals and residuals in each block decrease by more than three orders of magnitude. The relative error of import and export mass flow is less than 0.5%, and the flow is no longer changing.

3. Overall performance

Figure 3 shows the efficiency and pressure ratio characteristic curves of different HG models. It can be seen that at the design flow rate (7.6kg/s), with the existence and increase of HG, the efficiency and pressure ratio of model level both show a downward trend. However, when the flow rate increased to the near blocking point, the efficiency and pressure ratio of the model with Gap=0.2mm was the highest, and the efficiency and pressure ratio of the other models decreased with the increase of HG. If the flow continues to increase, the efficiency and pressure ratio of the model level will increase with HG. At this point, the efficiency and pressure ratio of all models decrease substantially compared to design points.

Figure 3. Efficiency and pressure ratio curve of models.

Figure 4 shows the efficiency and pressure ratio attenuation of models with HG compared with those without HG. From the flow rate (6.84–9.12) kg/s, the efficiency and pressure ratio of HG model were lower than those without HG, and HG increased, while the efficiency and pressure ratio decreased. At small HG, the flow increased and the attenuation degree decreased. At large HG, the flow rate increases and the attenuation degree increases. This is because, in the small HG model, the loss of gas in the boundary layer is weakened by the increase of leakage flow, while in the large HG model, leakage loss occupies a major position. At flow rate (9.12–9.88) kg/s, the model showed the opposite characteristics. The model efficiency and pressure ratio with HG were higher than those without HG, and the higher the HG was, the higher the efficiency and pressure ratio was. It indicates that HG has an adverse effect on the flow field when the compressor is running near the design point. When not running near the design point, HG is beneficial to the flow field.
4. Flow Field

4.1. Flow Field

Figure 5 shows the total pressure distribution of the model in the meridional plane at the design point, and the models without HG, 0.2mm and 3mm gap from left to right.

As can be seen from Figure 5, with the presence and increase of HG, significant low pressure loss occurs on the hub side of the stationary blade, especially from the bend outlet to the stationary blade outlet. In the middle and downstream of the stator flow passage, the area of low pressure formed by the mixing of leakage flow and main flow expands and the loss increases. Before the turn, the difference of gas pressure distribution in the flow channel was not obvious, especially for the model with small HG. After the turn, the difference of total pressure increased significantly. At the same time, there is also a low pressure area at the exit of the compressor stage, resulting in flow loss. At the design point, leakage flow is the main factor of aerodynamic loss. The larger HG is, the greater the pressure loss is.

Below, the velocity and entropy distribution of 5% blade height section in the No HG, 0.2mm and 3mm clearance models are analyzed at the blocking condition (flow rate was 9.88kg/s) The above row charts are the inlet channel of the model, and the below are the outlet channel of the model, from left to right are No HG, 0.2mm and 3mm HG (Figure 6 and Figure 7).
Because the three models are all at the blocking condition, a large range of low-speed zone appears in the blade root region of the flow field, which causes the flow loss. With the presence and increase of HG, the low-velocity gas near the stationary blade inlet gradually concentrated in the middle of the flow passage. According to the velocity distribution diagram at the static blade outlet, in models without HG and with small HG, low-speed gas is concentrated in the wake area at the downstream of the stationary blade. With the increase of HG, the low-speed area is separated from the blade, and the suction surface of the blade tends to be in the middle of the flow path. The effect of this phenomenon is that the models without HG and with small HG have a significant increase in entropy at the entrance of the stationary blade, while the models with large HG have a high entropy zone near the bend. When the compressor flow is too large, due to the pressure difference, the gas flows from the pressure surface into the suction surface, resulting in leakage flow. The leakage flow and the gas in the main flow area flow together along the flow direction. As the gas is affected by centrifugal force at the bend, the direction of movement is from radial to circumferential, and the two gases mix and mingle at the bend. The leakage gas at the inlet of the static blade can reduce the blockage of the flow field, correct the flow rate of the compressor, reduce the flow loss within a certain range, and make the high-entropy area change to the bend.

4.2. Stability Extension Mechanism
According to the results of numerical calculation, when the flow rate is 6.46kg/s, the flow field of the model with HG is stable, while the model without HG has stall phenomenon in the model. The following is the analysis of the total pressure and streamline distribution in the meridional plane of the two models (the left side is No HG, and the right side is HG=0.2mm model).
From the total pressure and streamline distribution of the two models, it can be seen that in the model without HG, there is an obvious area of low pressure on the hub side, which will continue to the exit of the bend, and there is a gas separation area. These low pressure zones and flow stall separation zones contribute to the instability of flow in the model stage. With HG, HG leakage flow will reduce secondary flow and vortex movement at the hub, reduce flow loss, stabilize the flow field, and improve compressor surge margin. Figure 10 shows the entropy distribution of the two models (95%, 50% and 5% height sections from top to bottom).

According to Figure 10, for the three height sections along the spanwise direction, the high-entropy regions of the model without HG are all larger than those of the model with HG. From the analysis of the distribution position of the high-entropy region, in the tip region, the high-entropy region of the model without HG is concentrated in the middle and downstream of the flow channel. This phenomenon can be explained by Figure 11. In the middle and downstream the flow channel of the model without HG, the low-velocity region of the fluid appears, resulting in separation and backflow. In the blade root region, the flow is very complex and harsh, and both models have high loss areas at the inlet of the stationary blade and the upstream of the flow passage. In the middle-leaf area, the high-loss area of the without HG model is concentrated in the upstream and the bend part of the flow passage. As can be seen from Figure 12, the flow angle of the gas at the flow passage varies greatly, and the gas has backflow phenomenon. At the entrance of the stationary blade of the model with HG (as shown by the arrow), the flow is separated. This is because the flow direction of the gas at the entrance is changed due to the presence of HG, but it does not spread, and the gas flows steadily in the entire flow field.
At the condition of small flow rate, the inlet angle of the compressor increases, the inlet flow field becomes uneven, the leading edge of the blade is separated locally, the flow passage on one side of the blade is blocked, and the gas is deflected. These low-energy fluids expand in the flow channel, resulting in a larger separation zone, which promotes the unstable development of the flow field and the loss of stage efficiency. In the model with HG, due to the pressure difference between the two sides of the blade, there is a strong leakage flow, and the leakage gas flows from the pressure surface to the suction surface, which alleviates the unevenness of the inlet passage, inhibits the development of stall disturbance of the flow to a certain extent, and makes the system more stable.

5. Conclusion
In this paper, HG is used to suppress gas stall and expand the range of stable working condition of compressor. This paper mainly draws the following conclusions:

1) At the design flow rate, the model level efficiency and pressure ratio both showed a downward trend as HG grew from zero to large. At the large flow rate, the model showed the opposite characteristics. The model efficiency and pressure ratio with HG were higher than those without HG, and the larger HG was, the higher the efficiency and pressure ratio was. It indicates that HG has an adverse effect on the flow field when running near the design point of the compressor. When not running near the design point, HG is beneficial to the flow field. The flow margin of the two groups of models with small HG and large HG was increased by 5% and 15% compared with the model without HG, and the comprehensive stall margin increased by 6.87% and 23.59% on average. Generally speaking, HG can play a role of compressor expansion stability, but at the same time at the cost of efficiency; The bigger HG is, the stronger the role of expanding stability is and the greater the efficiency loss is.

2) When operating at the unstable working conditions, the role of HG is to make the airflow in the high pressure zone flow into HG and then flow out of the low pressure zone, which improves the flow distribution in the blade passage, reduces secondary flows and vortices, and makes the flow field stable. However, when operating near the design point, the gas leakage flow in HG and its mixing with the momentum of the main flow become the main source of compressor loss, and the greater HG is, the greater the pressure loss caused by the leakage flow.

The study in this paper reveals the influence of static blade HG on the aerodynamic performance, stability expansion and flow field of centrifugal compressor, and it is found that HG can control the flow instability of gas at the bend, and it can be extended to other parts of turbine machinery with a large degree of bending (such as the L-shaped channel of the return channel between two stages of centrifugal compressor). Although HG plays an expanding stability role, it reduces the efficiency of the whole stage. The next design goal is to avoid the loss of efficiency while expanding the stability, and to apply it to the multi-stage compressor to ensure the reasonable matching of flow field between the stages. At the same time, the experiment will be used to verify the simulation.

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