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Numerical Simulation of Stall Suppression By Micro Air Injection In A Low-Speed Axial Compressor

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ABSTRACT

It is proved in the previous experiment that a micro jet injection (0.05% of main flow) in the tip region in front of compressor rotor could push the stall boundary to its left up to 5.8% in a three stage low speed axial compressor. To explore the mechanism of micro injection and its unsteady response by experiment is relatively difficult. Therefore the numerical simulation has been investigated to clarify the detailed flow structure at near and post stall conditions. The calculated performance line showed 2.06% of stall margin improvement by the injected air of only 0.045% of main flow compared to 3.14% improvement of experiment result at the same amount of injection. The local momentum of the injected mass flow is much greater then the main flow and leads to scrubbing velocity field near suction surface of blade and therefore suppressing the separation. The shifted location of the tip vortices toward downstream can also be observed.

INTRODUCTION

Stimulating the unsteady response of compressor system by changing its boundary with steady passive control method was another new idea of compressor stall suppression. The method integrates the advantage of both active and passive control because it can effectively extend the operating region without the loss in efficiency and robustness. Tiny injection in the rotor tip of the compressor is one possibility to realize such idea. It was proved in the previous experiment in a three-stage low-speed axial compressor system that a steady micro injection from the casing before rotor, with the amount of injected air of only few ten thousandth of the compressor flow rate, is able to enhance the compressor stability by lowering the mass flow rate at stall for up to 5.8%.[1,2] If the compressor was treated as a linear or quasi-linear system, 0.05% of injected flow could not bring such benefit to compressor characteristic with classical velocity triangle analysis. However, if the compressor system was treated as strong nonlinear system, tiny boundary transfer then could influence the system performance. We called it unsteady response of compressor system. In order to explain why such tiny air injection could bring benefit to the compressor stability, and to uncover the existence and the mechanism of unsteady response, experimental verification through comparison of various injection configurations in effecting the global compressor performance and detailed stall inception characteristics was deployed. The experiment results give the trend of injection as following:

- ✓ The control effect grows but get slower with flow rate of injected flow increased;
- ✓ A range of best injection angles exist and some injection angle has even worse effect when it could induce the compressor to stall early than the case without injection.
- ✓ The effect of stall control get better with the injection position closer to shroud and closer to rotor leading edge.

But the question remains of how the micro injection interacts with the flow in blade passages. This is the common question nowadays for the flow physics leading to stall and in our case the mechanism of unsteady response leading to stall suppression. Resolving this question experimentally needs the detailed measurement of the unsteady flow field at least in the rotor tip region which is still difficult to realize. Therefore numerical simulation was chosen to uncover the blade passage flow in the compressor tip region specifically through comparison of the computation results for the cases of with and without injection. There exist two difficulties, one is whether the stall inception procedure could be captured by numerical simulation, the other is whether the numerical compressor system could has the same response as experiment in responding to the micro injection so that the mechanism of unsteady response with micro injection could be clarified.

DESCRIPTION OF COMPUTATION DOMAIN

Table 1 Parameter of Three-Stage Axial Compressor

Rotational speed (rpm)	2400
Mass flow rate (kg/s)	2.6
Pressure rise coefficient	2.32
Outer diameter (mm)	500
Hub-tip ratio	0.75
Blade number of rotor/stator	60
Axial gap – rotor/stator and stage (mm)	8
Aspect ratio of rotor/stator	1.86
Tip clearance (% of tip chord)	3.4

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The design parameter of the 3 stage test compressor was shown in Table 1. Because the unsteady calculation is too time consuming, only the single rotor with axial injector was simulated. As shown in Figure 2, four injectors were located at the shroud of rotor 2 mm upstream of leading edge just the same as the experiment. In the three-dimensional unsteady viscous computation, based on the actual numbers of 4 injectors and 60 rotor blades, the computation for the numbers of 1 injector and 15 rotor blades can be accepted to simulate the unsteady injector-rotor flow. The injector domain was

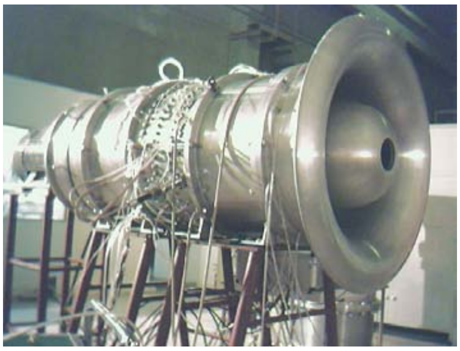


Figure 1 Compressor test rig

treated like stator and the sliding interface was used between injector and rotor domains. The computation started from steady scheme to gain the performance curve by closing the throttle valve and then changes to unsteady scheme at the near stall point and further into stall. The speed of injected flow was given the same as in the test case which is 64m/s.

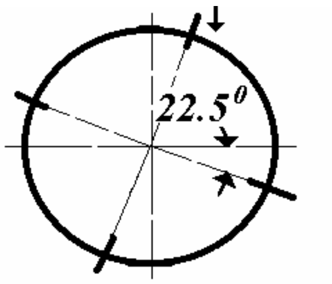


Figure 2 Distribution of injector

The traditional way of calculating the performance line depends on adjusting the back pressure at the outlet of compressor to get the whole characteristic line from choke to stall. But in stall-related calculation, especially the compressor has zero or negative slope of performance line at near stall point, back pressure adjust calculation method will get dyadic and failed. The throttle valve model defined as follows was accepted at this situation instead of back pressure adjusting. The model used here is just the same as the model used in Moore-Greitzer model.[3,4] At the end of each time-step, back pressure of the computational domain will be adjust from the following equation.

$$P_2 = P_{out} + \frac{\rho U^2 \phi^2 K_{t0}}{2K_{t1}} \qquad (1)$$

Where P_{out} is outlet pressure of throttle valve which is atmosphere pressure, ϕ is the massflow coefficient, K_{t1} the open of valve, and K_{t0} the start position of valve. $K_{t1} = 1$ means the start position of the valve and $K_{t1} = 0$ the valve is totally closed.

As shown in figure 4, the rotor passage was filled with hybrid grid, the region near the injector with unstructured hexahedral, and structured hexahedral was used to fill the other region of injector zone. 4 layer of the grid was used in the tip clearance. FLUENT UNS with the standard SIMPLE core method was used and RNG-k-ε turbulence model and a non-equilibrium wall function were applied to capture the interaction between complex leakage vortex and injection. For the unsteady computation, a second-order time accuracy scheme was used. For time resolution 20 steps was chosen in each rotor passage. Other computation details are shown in table 2.

After adjusting the back pressure at the end of the each time-step, the back pressure will jump up and get converge in the time-step. Stall occurred when back pressure fall with acceleration.

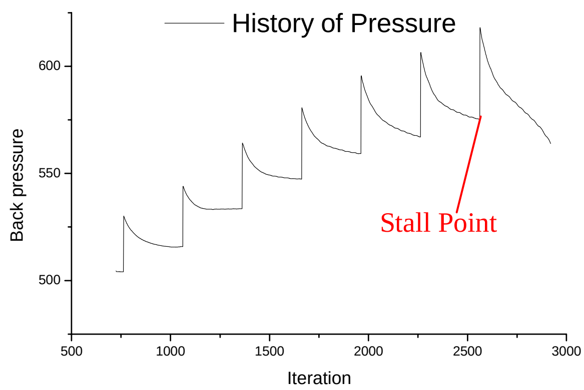


Figure 3 Definition of Stall Point

Table 2 Other computation details

Control equation	Unsteady non-compressible N-S equation
Number of the grid	1,400,000
Computation software	FLUENT UNS
scheme	Standard SIMPLE
Time step	20/rotor passage
CPU	4 PentiumIV 2.0
Parallel mode	MPI

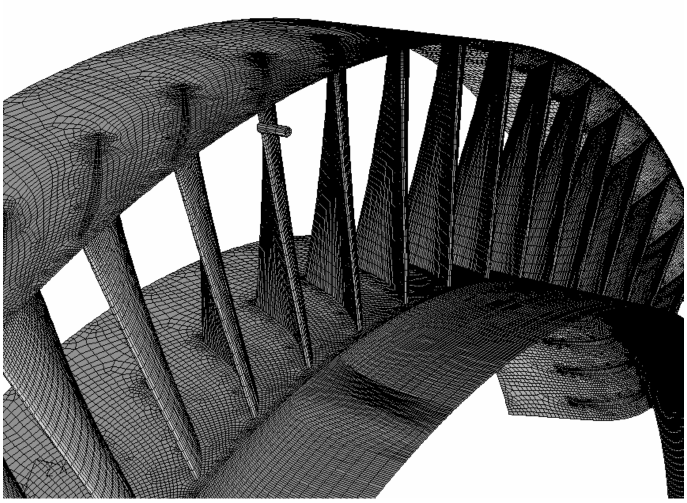


Figure 4 Computation grid

COMPUTATION RESULTS

First, the compressor performance curves with and without injection are compared. The experiment was done in three stage while the calculation was done in single rotor, therefore only massflow of stall point could be compared. The computation results showed a correct trend of stability enhancement through micro injection and the qualitative agreement with experimental data was obtained. The calculated mass flow coefficient at stall point with injection was 0.4119 while it was 0.4204 without injection. The stall boundary was thus pushed to the left by 2.06%. From the experiment data, the mass flow coefficient at stall point with injection was 0.4008 while it was 0.4138 without injection, meaning that the stall boundary was pushed to the left by 3.14%.

Then the detailed blade passage flow patterns computed at the same throttle position which gave different operating point as post-stall without injection and as just before stall with injection were compared as shown in Figure 7 and Figure 8. From the relative velocity contour at rotor tip region in the case without injection, we can see the separation line just before the leading edge. In the case with injection, although the injected mass flow is very limited, its local momentum is much greater than the main flow, so it leads to scrubbing velocity field near suction surface of blade and therefore suppressing the separation. The scrubbing can be seen more clearly through 3D path line in Fig.9. Looking at the relative velocity contour at the same throttle valve position which is just post-stall without injection and just near stall with injection (Fig.10 and Fig.11), we can see the formation of stall cell without injection and normal periodic flow field with injection. From the structure of tip clearance vortex, as showed in Fig.12 and Fig.13, the forward shifted location of the vortices can be observed for the case with injection, which gives a delaying effect to the inception of stall.

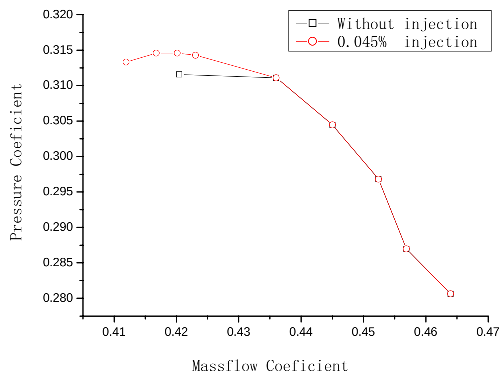


Figure 5 Performance Line by Calculation

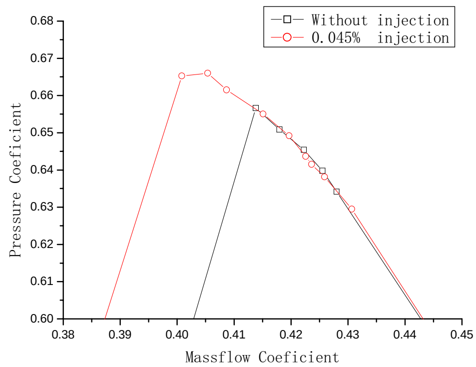
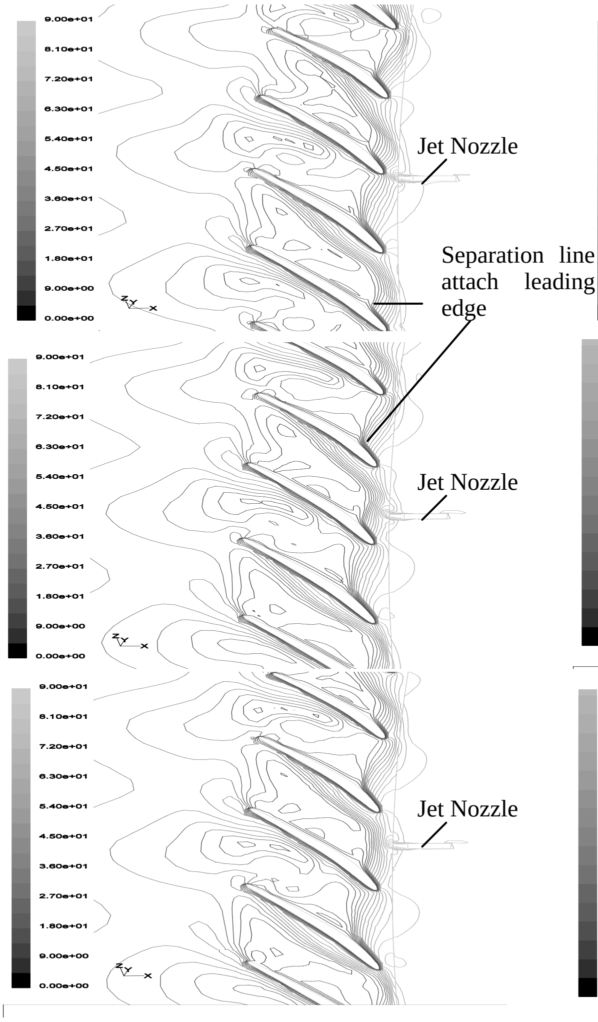


Figure 6 Performance Line by experiment



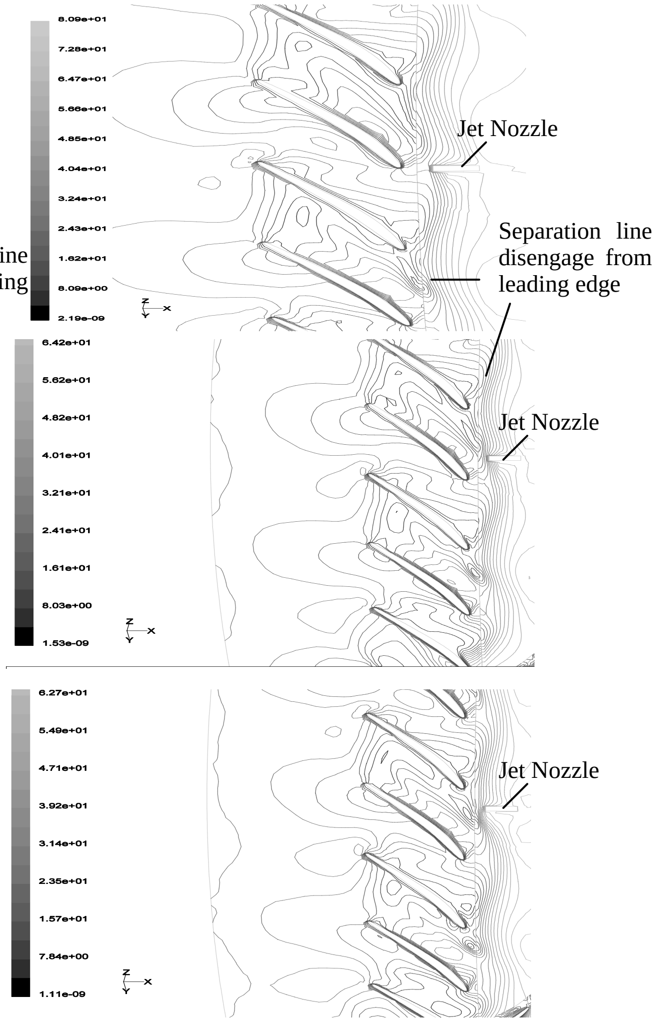


Figure 7 Unsteady velocity contour with injection

Figure 8 Unsteady velocity contour without injection

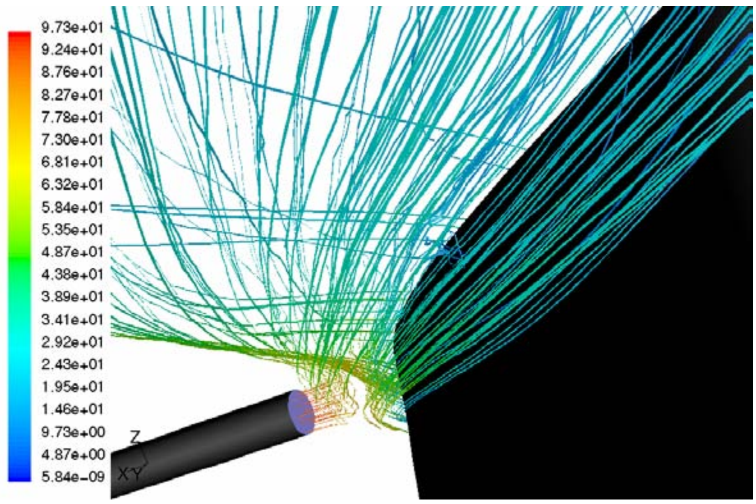


Figure 9 Scrubbing velocity field near suction surface of blade

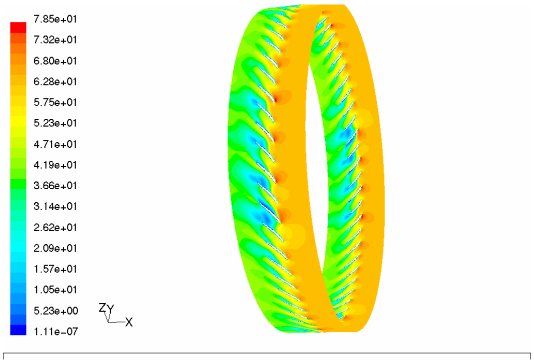


Figure 10 Relative velocity magnitude without injection

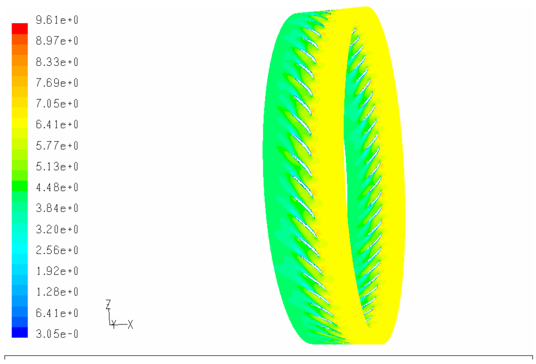


Figure 11 Relative velocity magnitude with injection

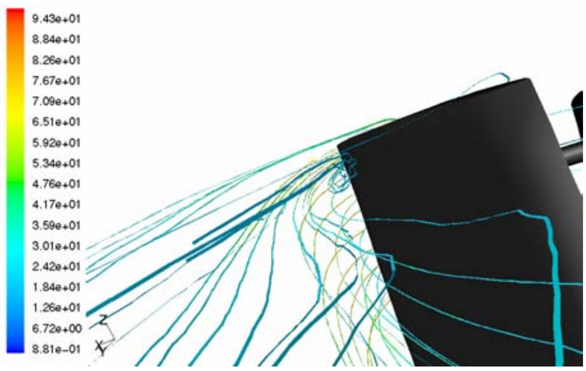


Figure 12 Tip vortex without injection

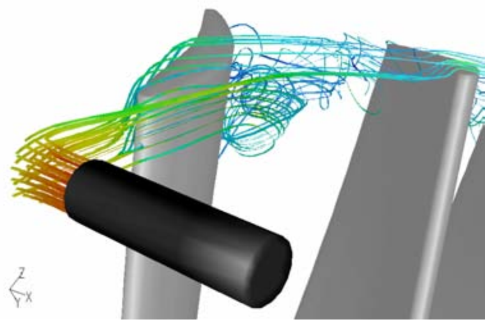


Figure 13 Tip vortex with injection

CONCLUTIONS

Numerical simulation has been used to explore the effectiveness and its underlying flow mechanism of a new micro air injection method to enhance the compressor stability. The results showed that RANS could simulate the phenomenon of rotating stall and the effectiveness of stall suppression by micro injection, that 0.045% of main flow could bring 2.06% of stall margin improvement by computation compared to 3.14% improvement of experiment result at the same injected flow rate. The local momentum of the injected mass flow is much greater than the main flow and leads to scrubbing velocity field near suction surface of blade and therefore suppressing the separation. The forward shifted location of the tip vortices can also be observed.

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