

Available online at www.sciencedirect.com**ScienceDirect**

Procedia Engineering 99 (2015) 484 – 490

**Procedia
Engineering**www.elsevier.com/locate/procedia

“APISAT2014”, 2014 Asia-Pacific International Symposium on Aerospace Technology,
APISAT2014

The Aerodynamic Design and Investigation of Loading Distribution of a Mixed Flow Compressor

Chen Xuanyu^{a,*}, Meng Xiangwei^b, Gui Xingmin^a, Jin Donghai^a

^aBeihang University, 37th Xueyuan Road, Haidian District, Beijing 100191, China

^bChina Aero-polytechnolony Establishment, 7th Jingshun Road, Chaoyang District, Beijing 100028, China

Abstract

In this paper, the design for the mixed flow compressor is based on the results of a S2 through flow aerodynamic design program and a general arbitrary curved blade design method for axial, centrifugal/mixed compressors. Three different mixed flow compressors with different circulation distributions were studied. The results show that different circulation distributions should be utilized from blade hub to tip. For blade hub, more loading in posterior area should be chosen, while for blade tip more loading in frontal area of the blade is available. With this loading distribution, the separation flow in blade hub is controlled, along with the reduction of separation flow in blade tip. The performance of the mixed flow compressor can be boosted with a more homogeneous distribution of aerodynamic parameters from blade hub to tip, a more homogeneous flow field and a higher pressure recovery coefficient.

© 2015 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license

(<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Peer-review under responsibility of Chinese Society of Aeronautics and Astronautics (CSAA)

Keywords: mixed flow compressor; aerodynamic design; loading distribution; numerical simulation; circulation distribution

1. Introduction

The mixed flow compressor has a structure between axial compressor and centrifugal compressor. It has the high flow capacity in the frontal area and high efficiency of axial compressors as well as high pressure rate of centrifugal compressors. Under the same working condition, the mixed flow compressors have less flow losses, a larger flow

* Corresponding author. Tel.: +86-134-0117-7346;

E-mail address: harrycxy123@163.com

coefficient and a higher efficiency compared to centrifugal compressors. The mixed flow type is more suitable for the compressors whose sizes are limited.

The researches on mixed flow compressors were carried out in 1950s. However, the investigations in this very field were not adequate and the mixed flow compressor didn't show a good performance in early days because of the limit of computational and experimental methods. The CFD technology provides an advanced method for the research of mixed flow compressors. It embraced a booming development for the research of mixed flow compressors. Musgrave and Plehn [1] designed a single stage mixed flow compressor which had a pressure ratio of 3.02 and efficiency of 0.91 for its rotor, which was higher than any mixed flow compressor at that time. Monig [2,3,4] designed a mixed flow impeller which has a pressure ratio of 5, and the experiment research was carried out later. The result showed that the impeller had a narrow working range and the outlet Mach number was too high for diffuser. The compressor failed to achieve a good performance. Mert Cevik [5] from Middle-East Technology University in Turkey designed and modified a mixed flow rotor based on a centrifugal impeller. The result showed that the mixed flow impeller had a better performance. In 2011, Mert Cevik designed a mixed flow compressor for a gas turbine engine [6]. By analyzing its flow field, a shock structure and the obstruction of shock and boundary layer can be seen clearly in its flow passage, which may have a bad effect on its performance.

The study of mixed flow compressor in China has started only in recent years and recorded investigations cannot be substantially founded. Liu Baojie and Gao Xing [7,8] analyzed two high specific speed centrifugal and mixed flow compressors. The overall performances were also studied. The result showed that there were similar flow structures in two impellers' inducers. Mixed flow compressor achieved better performance and lower tip leakage loss, and flow field outlet was more uniform in mixed flow impeller than in centrifugal impeller. In the same year, Liu Baojie [9] investigated the impact of loading distribution in blade hub and blade tip on outlet flow homogeneity. The result showed that increasing hub design circulation could make impeller achieve better performance and lower tip leakage loss, and make flow field at outlet more uniform, but increasing tip design circulation could make impeller achieve higher ratio of total pressure in surge condition.

As the design tendency of compressors are pursuing higher through flow capability and higher loading capability. The design of mixed flow compressor will get a higher application in the future. So it is necessary to carry out deeper and more comprehensive investigations on mixed flow compressors.

2. Methods

The design for a single stage mixed flow compressor and the choice of design parameters are based on the results of a S2 through flow aerodynamic design program and a general arbitrary curved blade design method for axial, centrifugal/mixed compressors [10,11]. This program has succeeded in designing several compressors, such as ATS-2. After through flow design and 3-D CFD simulation analysis, the conclusions were drawn with comprehensive analysis. Numerical simulation software NUMECA was used to simulate the 3-D flow field of the mixed flow compressor and analyze its performance. The loading distribution can be regarded as circulation distribution. By studying three different impellers with different circulation distributions in chord direction, the impact of loading distribution on the performance of mixed flow compressor can be observed. Table 1 shows the design parameters of the mixed flow compressor.

Table 1. Parameters of mixed-flow compressor

	Designed value
Pressure ratio	2.8
Adiabatic efficiency	0.87
Corrected mass flow (kg/s)	16.988
Inlet total temperature (K)	526.78
Inlet total pressure (Pa)	663295.5

3. Flow passage and computational mesh

The shape of the flow passage has great influence on the performance of a compressor. For centrifugal compressors, the curvature radius of the shroud is small at inlet region, so that boundary layer separation occurs easily with the reduction of efficiency. However, the mixed flow compressors have a larger curvature radius at inlet region, which decreases the probability for separation flow. By analyzing both through flow computation and 3-D simulation results, the flow passage is showed in Fig. 1. In order to increase the solidity of the compressor in posterior area, splitter was utilized from 40% chord position to trailing edge of the rotor.

A 3-D simulation software NUMECA is used to simulate the 3-D flow field of the mixed flow compressor. NUMECA has an excellent performance for its simulation ability and computation accuracy for turbo machineries. Spalart-Allmaras turbulent model is used when solve Navier-Stokes equations. The computational mesh is showed in Fig. 2 and the total grid number is 795687.

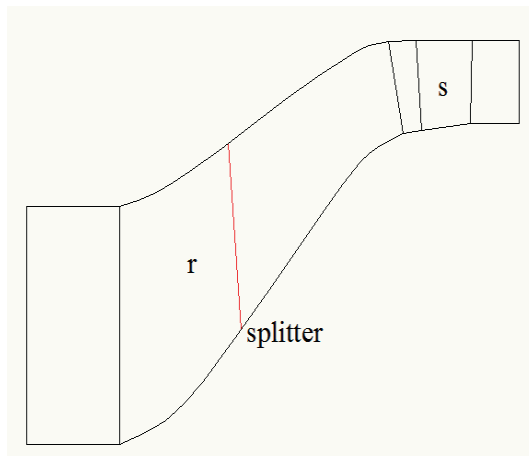


Fig. 1. Flow passage of mixed flow compressor

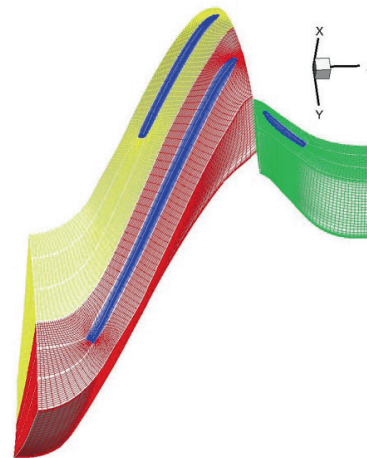


Fig. 2. Computational mesh

4. The impact of loading distribution

4.1. Loading distribution

The circulation distribution can be regarded as loading distribution. By giving different mixed flow rotors with different circulation distribution, the impact of loading distribution can be studied. In this paper, three mixed flow compressors were designed with the same pressure ratio along the span direction, but with different circulation distribution in chord direction. Fig. 3 to Fig. 5 show the circulation distributions of the three compressors. For the three compressors, L1 has more loading in posterior area from blade hub to tip. L2 has more loading in frontal area from hub to tip. Different circulation distribution was utilized for L3 from hub to tip. For blade hub, L3 shares the same distribution with L1 and the same distribution with L2 in blade tip. The circulation distribution in 20%, 50% and 80% span position is abided by arithmetic progression in the same chord position.

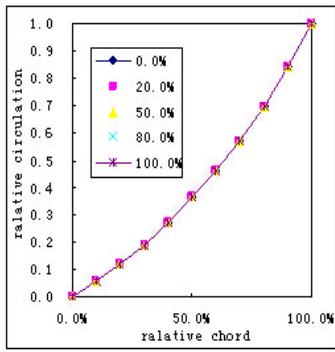


Fig. 3. Circulation distribution of L1

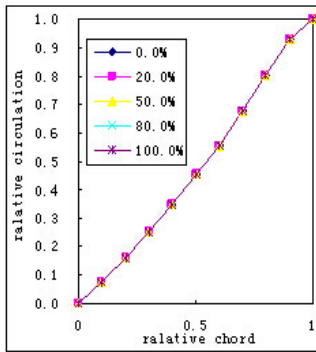


Fig. 4. Circulation distribution of L2

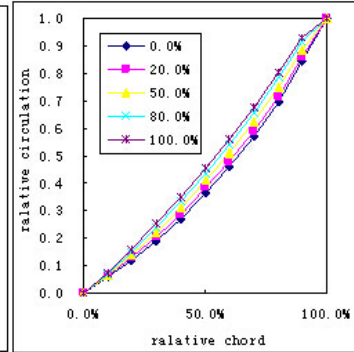


Fig. 5. Circulation distribution of L3

4.2. Result and discussion

Fig. 6 demonstrates the performance of the three compressors. The results indicate that compressor L3 has the best performance with the most mass flow rate of 18kg/s, the highest pressure rate of 2.72 and the highest climax adiabatic efficiency of 0.95. L1 has the widest surge margin but the lowest pressure ratio. L2 has a pressure ratio between L1 and L3, but its climax efficiency is less than 0.89.

Fig. 7 to Fig. 10 present the distribution of total pressure, the total temperature, the absolute flow angle and the total pressure recovery coefficient along the span direction at outlet. The compressor L3 with different circulation distribution from hub to tip has a more homogenous parameters distribution at outlet by comparing to the other compressors, which means it has a more homogenous flow field at outlet. Besides, the compressor L3 has the highest total pressure and total temperature at outlet.

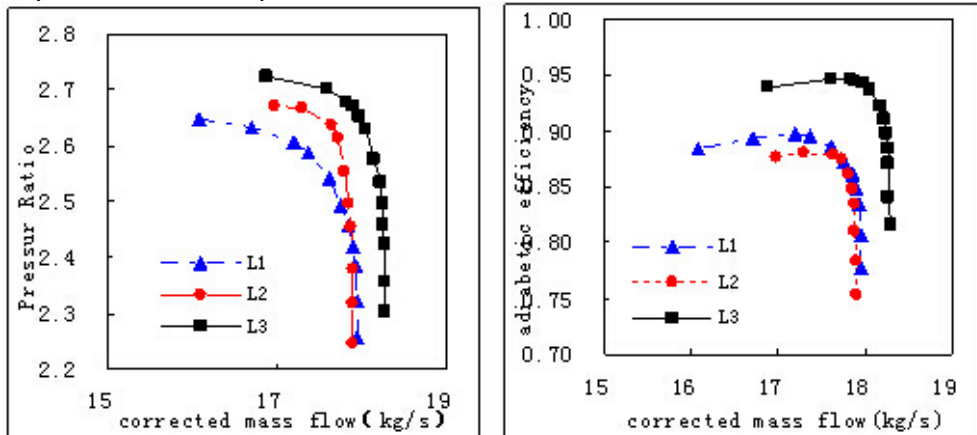


Fig. 6. Performance of the three compressors

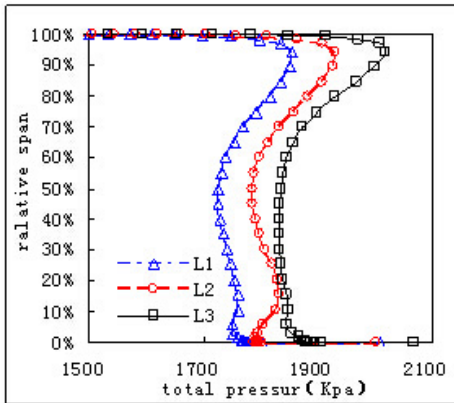


Fig. 7. Distribution of outlet total pressure

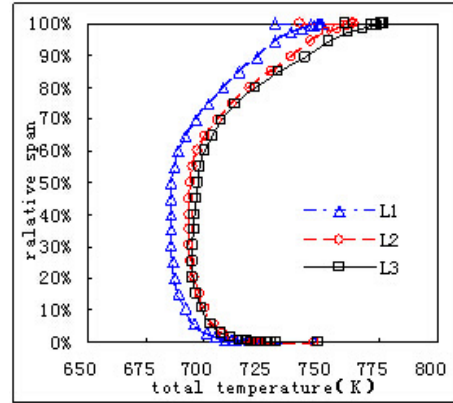


Fig. 8. Distribution of outlet total temperature

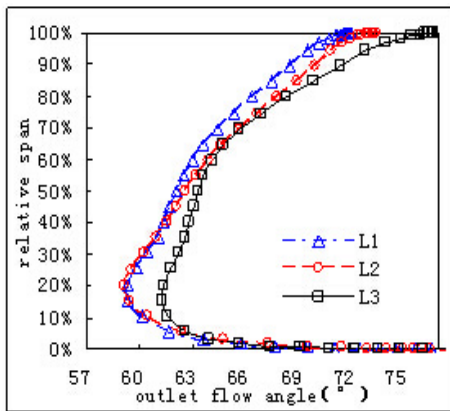


Fig. 9. Distribution of outlet flow angle

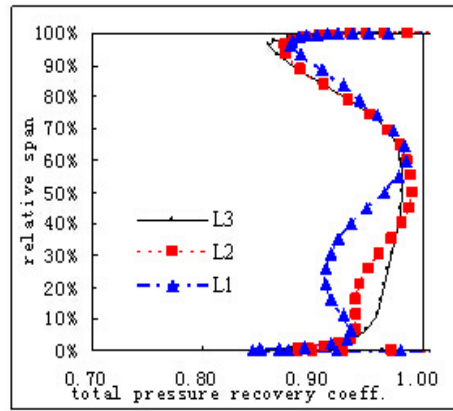


Fig. 10. Distribution of total pressure recovery coefficient

With different circulation distribution, the compressors have such different performances. The reason for this can be explained as followed: For blade hub of the impeller, the rising of the hub line is not very violent in frontal area. The flow in blade hub is turning smoothly in the frontal area, which means the centrifugal force cannot be greatly contributed to the pressure rise in frontal area. But with rake ratio of the hub line is getting bigger in posterior area, the centrifugal force can be fully applied to enhance the pressure rising capability. On the other hand, if more loading in frontal area for blade hub with less centrifugal force, the blade would be over-bended, which will cause the separation flow in the suction side of the blade, causing the reduction of efficiency. So in this case, more loading in posterior area with less loading in frontal area can be available for blade hub while for blade tip area, the situation is on the opposite.

Fig. 11 to Fig. 13 present the flow field of the three compressors. The results imply that a separation area can be detected in the suction side of the rotor tip. But the L3's separation flow is smaller in such area compared to L1 and L2. On the hub region of L2, the rotor turns to be over-bended owing to the loading in frontal area. The separation flow can also be seen in the middle span region of L2, which will increase flow losses.

Above all, considering the changing of the mixed flow compressor's flow passage, the loading distribution like L3 will be more suitable. On one hand, since the hub line rises slowly in frontal area, the blade hub can be designed to increase loading in posterior area, which can be adapted to the changing of passage. On the other hand, the centrifugal force with the rising of the passage and the high blade velocity can embrace the pressure rising capability

in the frontal area of the tip. Besides, by decreasing the loading in posterior area, separation flow in blade tip area can be controlled.

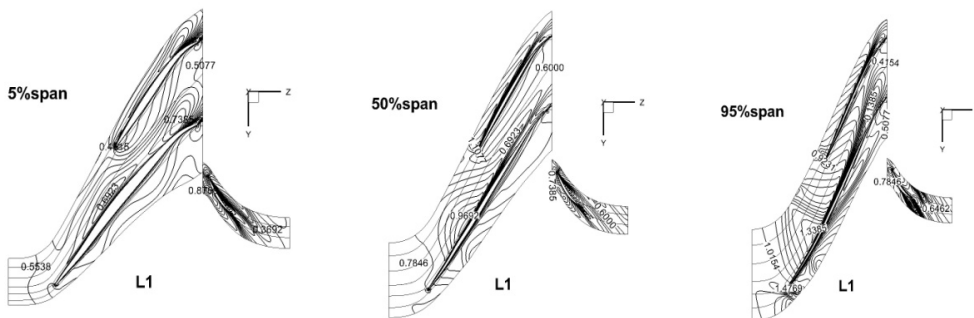


Fig. 11. Relative Mach number of L1

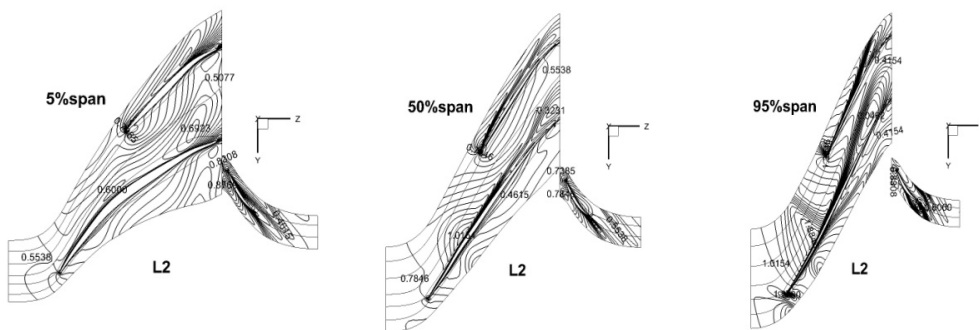


Fig. 12. Relative Mach number of L2

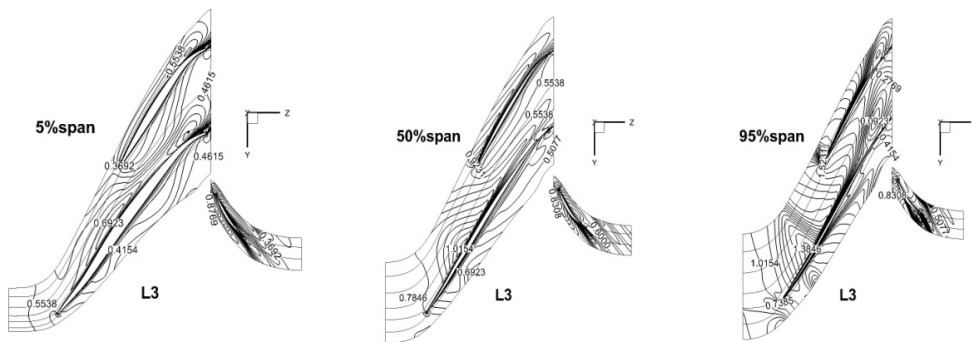


Fig. 13. Relative Mach number of L3

5. Conclusions

In this paper, the design for mixed flow compressors and the choice of design parameters are based on the results of a S2 through flow aerodynamic design program and a general arbitrary curved blade design method. By demonstrating three different mixed flow compressors with different circulation distribution along the chord direction, the influences of loading distribution on compressor's performance and flow homogeneity are studied. The results are as followed:

- Different circulation distribution should be utilized from blade hub to tip of the impeller. For blade hub, more loading in posterior area should be chosen, while for blade tip more loading in frontal area of the blade is available. By using this kind of loading distribution, the separation flow in blade hub is controlled and the area of separation flow in blade tip is decreased. The performance of the mixed flow compressor can be boosted with a more homogeneous distribution of aerodynamic parameters from blade hub to tip, a more homogeneous flow field and a higher pressure recovery coefficient. The compressor can achieve higher adiabatic efficiency.
- Increasing circulation in posterior area for blade hub and increasing loading in frontal area for blade tip can make the mixed flow impeller more adapted to the changing of flow passage. Centrifugal force can be adequately applied to achieve higher pressure ratio.
- After the 3-D simulation and computation, the compressor can have a highest pressure ratio of 2.72 which is a little bit lower than the expected value. But the compressor can have an adiabatic efficiency of 0.93 in working condition which is much higher than the designed value of 0.87.

Acknowledgements

The work was supported by National Natural Science Foundation (51006005, 51236001).

References

- [1] D.S.Musgrave, N.J.Plehn, Mixed-flow compressor stage design and test results with a pressure ratio of 3:1, *J. Journal of Turbomachinery ASME*, 1987, Vol 109.
- [2] Monig, Broichhausen, K. D, Gallus, H. E, Application of Highly Loaded Single-Stage Mixed-Flow Compressors in Small Jet-Engines, R. AGARDCP 421. 1987.
- [3] Mönig, W.Elmendorf, H.E.Gallus, Design and Rotor Performance of a 5:1 Mixed-Flow Supersonic Compressor, *J. Journal of Turbomachinery ASME* 1993, Vol 115.
- [4] Cai Xu, Huang Shengqin, Development of Foreign Diagonal Flow Compressor Design Technology, *J. Popular Science and Technology*, 2012(6); 14-154
- [5] Mert Cevik, Design and Optimization of a Mixed Flow Compressor Impeller Using Robust Design Methods, D. 2009.
- [6] Mert Cevik, Oguz Uzol, Design Optimization of a mixed Flow compressor Impeller for a small turbojet engine, *J. Aircraft Engineering and Aerospace Technology*, 2011.
- [7] Liu Baojie, Gao Xing, Analysis of Flow Feature in High Specific Speed Transonic Centrifugal/Mixed-Flow Compressor, *J. Aeroengine*, 2008, Vol 34
- [8] Gao Xing, Liu Baojie, Analysis of Flow in a High Specific Speed Mixed Flow Compressor, *J. Journal of Aerospace Power*, 2008, Vol 23.
- [9] Gao Xing, Liu Baojie, Effects of Circulation Spanwise Distribution on High Specific Speed Mixed Flow Impellers, *J. Journal of Engineering Thermophysics*, 2008, Vol 29
- [10] Ji Guofeng, Gui Xingmin, A Blade Design Method for Axial/Centrifugal Compressor Airfoils Using Arbitrary Camber Lines, *J. Journal of Aerospace Power*, 2009(1):24-1
- [11] Ji Guofeng, The Apply of General Blade Design System for Axial/Centrifugal Compressors, D. 2009