

Research Article

Study of High Efficiency Flow Regulation of VIGV in Centrifugal Compressor

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Variable inlet guide vane (VIGV) is used to control the mass flow and generate prewhirl in centrifugal compressors. Due to the tip clearance of the guide vanes and the defect of the traditional guide vane profiles, the mass flow regulation of VIGV is limited, resulting in a large waste of compressed gas. Two kinds of inlet flow channels were proposed to eliminate the influence of tip clearance. These structures were numerically investigated at different setting angles. The results show that the improved channels not only expand the range of mass flow regulation, but also reduce the power and increase the efficiency of the compressor. Ten kinds of guide vane profiles, including different thickness distribution, camber line profile, were selected to compare with the original one and with each other. In the premise of ensuring the performance of compressor, the best guide vane profile was selected. The results show that reducing the guide vane thickness, increasing the guide vane camber angle, and increasing the distance between the maximum camber position and the leading edge of guide vane can help expand the range of mass flow regulation. The achievement of this research can effectively improve the flow regulation ability of VIGV and the performance of compressor.

1. Introduction

In order to adapt to climate change and to meet the user requirements, the gas mass flow in actual operation of a centrifugal compressor needs to be regulated normally [1]. Variable inlet guide vane (VIGV) in the first stage of a centrifugal compressor is one of the effective ways to realize this function [2]. However, the regulating ability of traditional VIGV is very limited, resulting in a large amount of compressed gas that has to be discharged without effective use because of overproduction, especially in winter, up to 30% in some cases [3]. So it is very important to develop high efficiency VIGV device to solve the problem.

The purpose of the flow regulation is achieved with the flow area change and prewhirl generation of inlet gas by turning the VIGV angle in the operation of the centrifugal compressor [4]. However, a part of gas flow near the inlet channel wall cannot be controlled because of the tip clearance when the VIGV turns into a certain angle, especially at the large setting angle [5].

As the guide vane rotating to a certain angle, in order to avoid the collision between the guide vane and the casing wall, there must be a tip clearance on the top of inlet guide vane. Therefore, it is necessary to make the top of guide vane into a circular arc shape to match the casing wall when it turns an angle. When the fluid flows through the inlet guide vane passage, the pressure between the suction side and the pressure side of guide vane is different. It will lead to a portion of gas to climb over the tip clearance on the top of guide vane and then mix with the mainstream. This part of the gas cannot be regulated by the guide vanes, and the mix may cause some extra flow losses.

In addition, the shape of the VIGV is also a key factor to affect the flow regulation. Most VIGVs have symmetric vane profiles and create similar inlet flow characteristics at positive and negative prewhirls. At nonzero setting angles, flow experiences a strong suction side acceleration in the vicinity of the leading edge. The subsequent large deceleration can cause massive flow separation already at low incidence, which limits the useful operating range of VIGV [6]. In

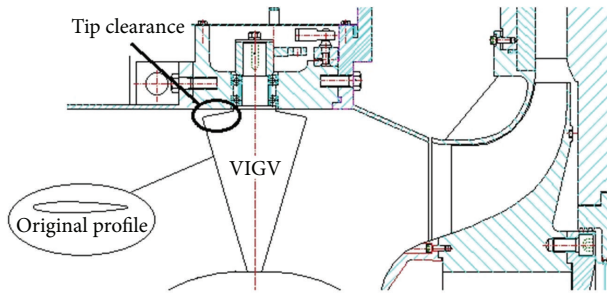


FIGURE 1: Sketch of VIGV in centrifugal compressor.

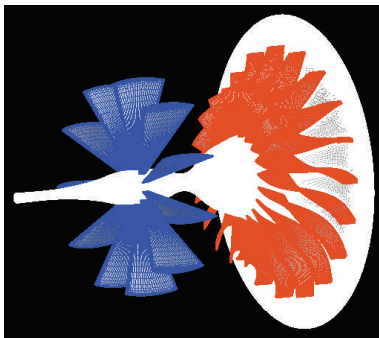


FIGURE 2: Mesh division of original model.

order to solve these problems and improve the regulation performance of VIGV, the thickness and camber and the position of maximum camber of guide vane were studied to find the most suitable profile, thereby expanding the flow regulation range of VIGV and improving the performance of the compressor.

The aim of this paper is to eliminate the influence of the tip clearance and select the best guide vane profile to achieve the optimal flow regulation [7].

In this paper, a centrifugal compressor (the first stage) in operation of one factory was provided as the research object. In the operation of this compressor, a large amount of compressed gas was often wasted due to the limitation of the regulating capacity of the inlet guide vanes. The compressor is composed of an inlet chamber, a VIGV system of 11 symmetrical straight vanes, an impeller of 19 rear curved semi-open impeller blades, and a diffuser. Figure 1 shows the sketch of this compressor.

2. Numerical Calculation Method

The model of the compressor, including the VIGV system and the impeller, was developed by the Pro/E software. High quality structural grid was created by NUMECA Autogrid5 [8]. The structure of grid is H-I, and the total number is about 16 million in the whole flow passage. In this paper, the same mesh topology and the number of grids were used for all the computational model. Figure 2 shows the mesh division of original model.

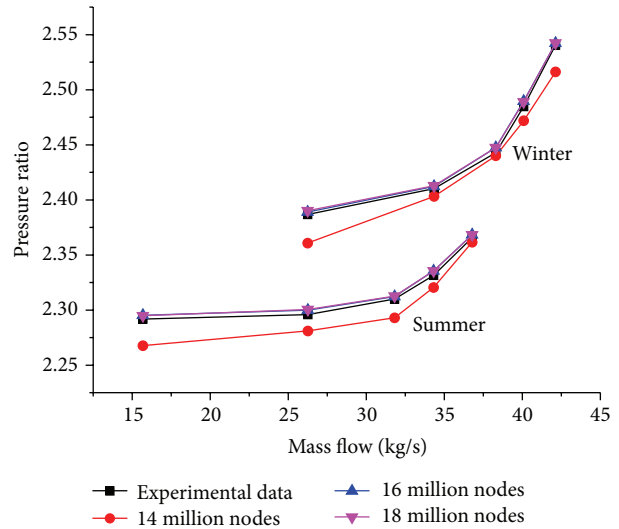


FIGURE 3: Comparison of pressure ratio curve in different number of grid nodes and experimental data.

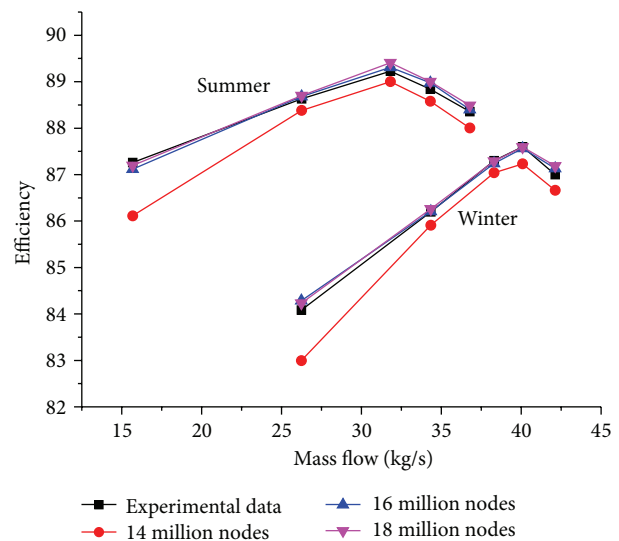


FIGURE 4: Comparison of efficiency curve in different number of grid nodes and experimental data.

In order to verify the accuracy of numerical calculation, three different numbers of grid nodes (14 million nodes, 16 million nodes, and 18 million nodes) and the original experimental data in the real operation process of the compressor provided from the factory were used to compare as shown in Figures 3 and 4. The comparison result shows that the numbers of 16 million nodes and 18 million nodes agree quite well with the original experimental data. It is clear that 16 million nodes can meet the requirement of calculation and the numerical method used in this paper is reliable.

The performance at different guide vane setting angles (-20° , 0° , 20° , 40° , 60°) in summer and winter was analyzed by means of NUMECA Fine [8]. The time-averaged Navier-Stokes equations were solved by time marching method, with the Spalart-Allmaras turbulence model. The y^+ was limited

TABLE 1: Calculation parameters and boundary conditions.

Item	Setting
Working medium	Air
Impeller speed	7460 r/min
Design point mass flow	32.29 kg/s
Inlet total temperature	303 K in summer 263 K in winter
Inlet total pressure	97000 Pa
Turbulent viscosity	$5 \times 10^{-5} \text{ m}^2/\text{s}$
Inlet condition	Axial inlet flow
Outlet condition	Mean static pressure

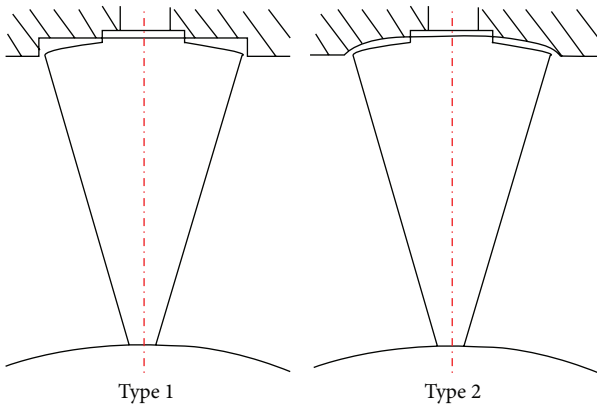


FIGURE 5: Two kinds of improved inlet flow channels.

to 10 as the requirement of low Reynolds number turbulence model according to the recommendation of NUMECA. The convergence of the algorithm was accelerated by using the full multigrid and implicit residual smoothing technique. The calculation parameters and boundary conditions were shown in Table 1.

3. Modification of Inlet Flow Channel

In order to eliminate the influence of the tip clearance of the guide vanes on the performance of the flow regulation, two kinds of inlet flow channels were proposed, as shown in Figure 5. Type 1 is to wrap the tip clearance in a right angle annular channel. Type 2 is to wrap the tip clearance by the circular arc annular channel. In order to verify the validity of these two improved channels, the same numerical calculation method was used to analyze and compare the performance of the two modified channels with the original structure.

From Figure 6, we can see that the two improved channels can reduce the flow rate at the large setting angle, so that it can help to expand the range of mass flow regulation. The adjustment range of Type 2 is significantly higher than that of Type 1. The regulation range of Type 2 is expanded by 15.19% in summer and by 9.16% in winter.

As can be seen from Figure 7, the improved channels have no effect on the power of the compressor at low setting angle of VIGV, but the power can be reduced with the increase

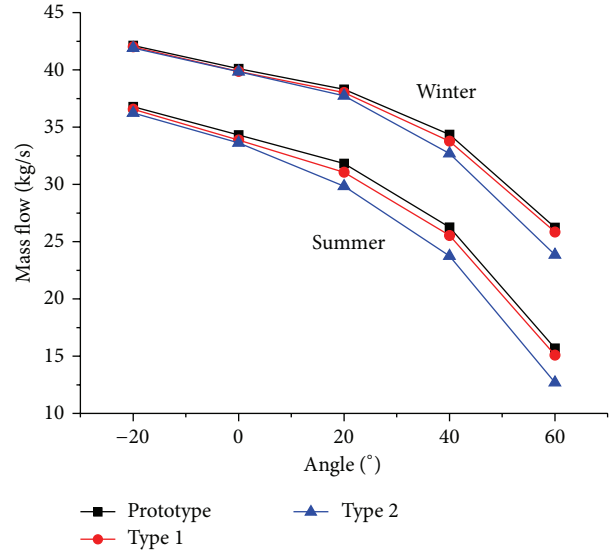


FIGURE 6: The change of mass flow with the setting angles.

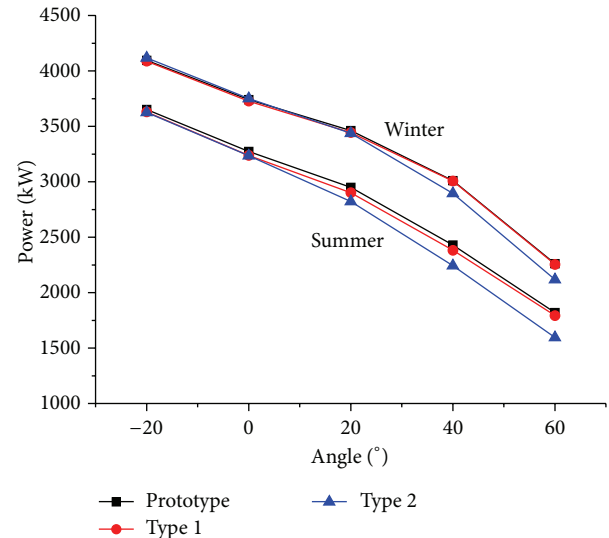


FIGURE 7: The change of power with the setting angles.

of the setting angle. Type 2 makes a lot of power reduction especially in summer, while Type 1 is negligible. As can be seen from Figure 8, the improved structure channel has little effect on the pressure ratio of the compressor. Figure 9 shows the influence of the improved channels on the efficiency of the compressor. The improved structures can significantly improve the efficiency of the compressor, especially in winter, and the higher the setting angle, the higher the efficiency.

The two improved channel structures (Figure 5) wrap the top clearance of the guide vane and thus the leakage of the gas is effectively controlled. As a result, the regulating ability and the performance of the compressor are improved. Although Type 1 can reduce the leakage of gas at the top of the guide vane, there is still a gap left between the vane tip and the box, so that a portion of gas enters the gap, generates flow separation, and increases the flow losses. In the structure

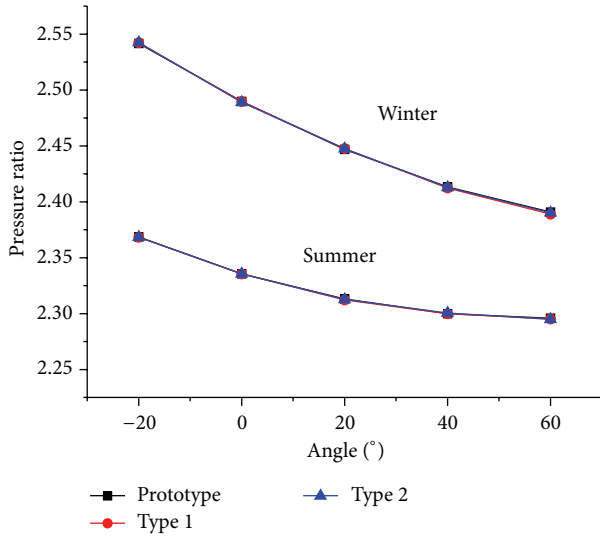


FIGURE 8: The change of pressure ratio with the setting angles.

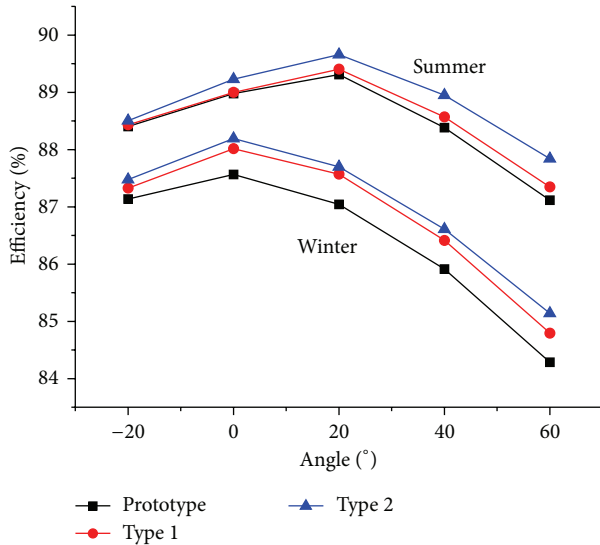


FIGURE 9: The change of efficiency with the setting angles.

of Type 2, the top of the guide vane and the casing wall cooperated with each other so that the secondary flow is limited to the minimum. Obviously, Type 2 is better than Type 1 in that it can not only expand the range of the flow regulation, but also increase the compressor efficiency.

4. Selection of the Guide Vane Profile

Considering the vane thickness and camber, ten kinds of NACA profiles were selected for the study. The same numerical calculation method was used for the flow analysis of these blades with Type 2 channel structure, and the flow regulation range chart was drawn.

In order to test the effect of the thickness of the guide vane on the flow regulation, three kinds of straight NACA profile with different thickness were selected, as shown in

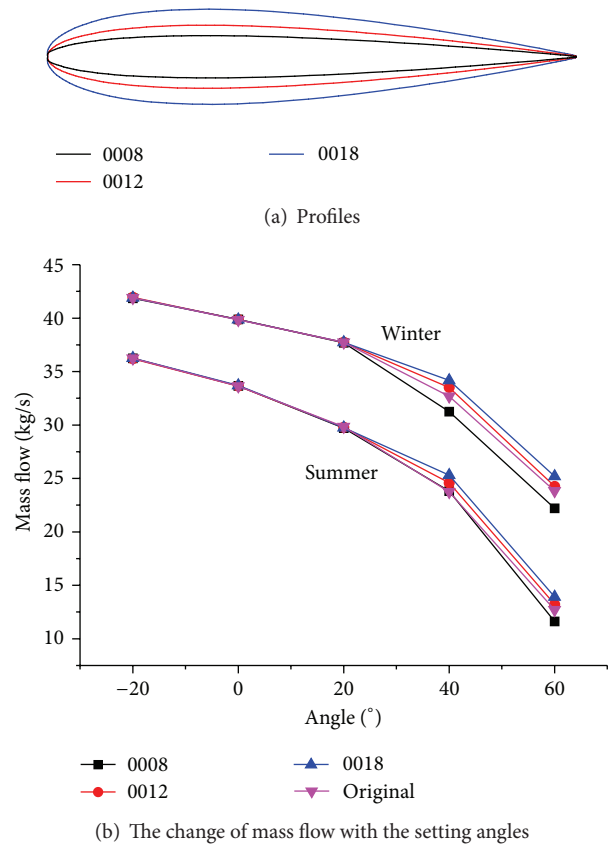


FIGURE 10: Straight guide vanes with different thickness.

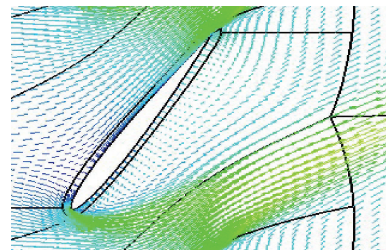


FIGURE 11: Velocity vector distribution of 0008 at 60° setting angle.

Figure 10(a). Figure 10(b) shows the flow regulation range of these three types of profile, and the comparison with that of the original. As can be seen from the figure, the flow regulation range of the three kinds of profile is the same as that of the original one when the guide vane setting angle is less than 20 degrees. The flow regulation range of the guide vanes is increased with the decrease of the profile thickness when the guide vane setting angle is greater than 20 degrees.

Figures 11 and 12 show the velocity distribution of 0008 and 0018 at 60° setting angle. From the figures, it can be seen that the speed of gas flow of 0018 is obviously higher than that of 0008. It is because the greater the thickness of the guide vane, the better the performance of the variable angle of attack, so that the flow in the guide vane channel will be more smooth. In contrast, when the gas flows through the thin guide vane, the flow on the suction surface of the guide vane

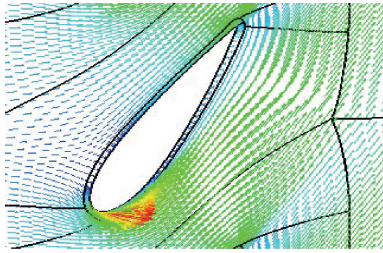


FIGURE 12: Velocity vector distribution of 0018 at 60° setting angle.

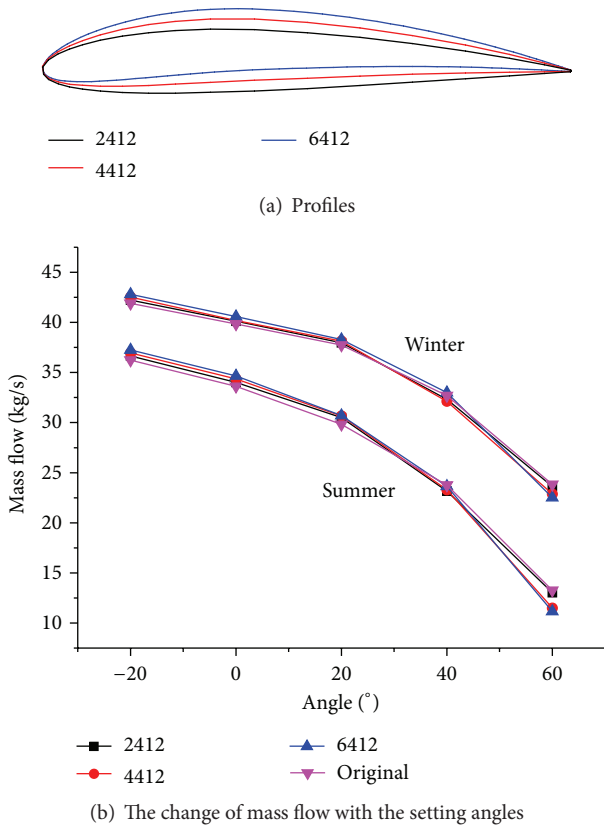


FIGURE 13: Different camber guide vanes.

is easy to separate, resulting in a great flow loss. Therefore, reducing the thickness of the guide vane can help us to enlarge the flow regulation range of VIGV, but it may increase the flow loss.

In order to test the effect of the camber of the guide vane on the flow regulation, three kinds of bent NACA profile with different camber were selected, as shown in Figure 13(a). Figure 13(b) shows the flow regulation range of these three types of profile, and the comparison with that of the original. It can be seen from the figure that whether in the large setting angle or in the small setting angle, the flow regulation range of the three kinds of profile is improved to some extent. Among them, the maximum camber 6412 profile flow regulating range is the biggest, and camber minimum 2412 flow regulation scope changes not obviously. Therefore, the

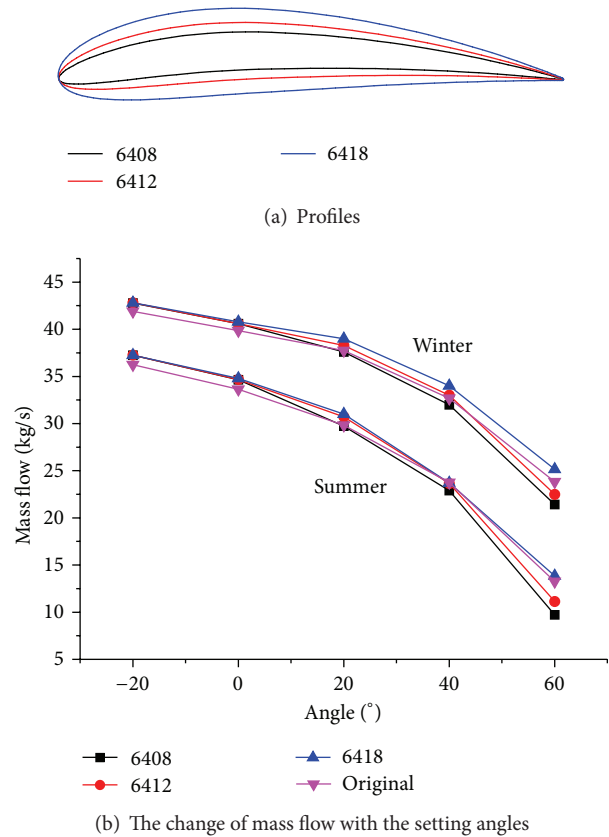


FIGURE 14: Camber guide vanes with different thickness.

increase of guide vane camber can help us to expand the range of flow regulation.

In order to test the effect of thickness of the bent guide vane on the flow regulation, based on the 6412 profile, we adjust the thickness of bent guide vane (as shown in Figure 14(a)) and compare the flow regulation range with the original one (as shown in Figure 14(b)). As can be seen from the figure, the same as the case of the straight profile, the greater the thickness of the guide vane, the smaller the flow adjustment range, and the smaller the thickness of the guide vane, the wider the flow adjustment range. The flow regulation range of 6418 is less than the original one. Although 6408 can increase the flow regulation range of the guide vanes, performance calculation indicates that the efficiency of the compressor is greatly decreased at 60° setting angle, because a strong vortex is generated on the suction surface of the guide vane; the flow separation loss is greatly increased, as shown in Figure 15. Therefore, increasing or decreasing the thickness of 6412 is not conducive to the flow regulation of guide vane.

Based on the 6412 profile, to adjust the maximum camber position of profile (as shown in Figure 16(a)), and to compare the flow regulation range with the original one (as shown in Figure 16(b)), it was found that the curves nearly coincide together for these three profiles and they can improve the flow regulation scope of VIGV. By comparing the three profiles, 6512 has a slight advantage, so the maximum camber location

TABLE 2: Mass flow, the mass flow rate change ratio, and efficiency at 60° setting angle.

Profile	Summer			Winter		
	Mass flow (kg/s)	Mass flow change ratio (%)	Efficiency (%)	Mass flow (kg/s)	Mass flow change ratio (%)	Efficiency (%)
Original	13.265	0	87.116	23.838	0	84.285
0008	11.616	-12.43	84.644	22.6	-5.19	83.773
0012	12.7	4.24	87.376	24.271	1.82	84.903
0018	13.92	4.94	88.074	25.2	5.71	86.000
2412	13.031	-1.76	87.057	23.617	-0.927	84.207
4412	11.8	-11.04	86.444	22.874	-4.04	83.504
6412	11.49	-13.38	85.763	22.4	-6.03	83.084
6408	10.01	-24.54	80.740	21.411	-10.18	81.580
6418	13.856	4.46	87.758	25.162	5.55	84.526
6312	12.11	-8.71	84.607	22.52	-5.53	82.207
6512	10.95	-17.45	87.821	22.016	-7.64	85.021

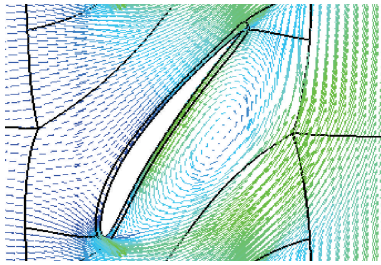
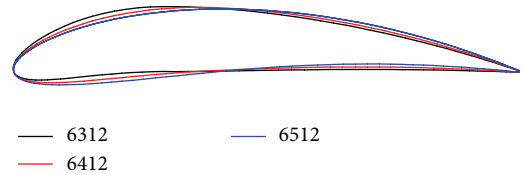


FIGURE 15: Velocity vector distribution of 6408 at 60° setting angle.

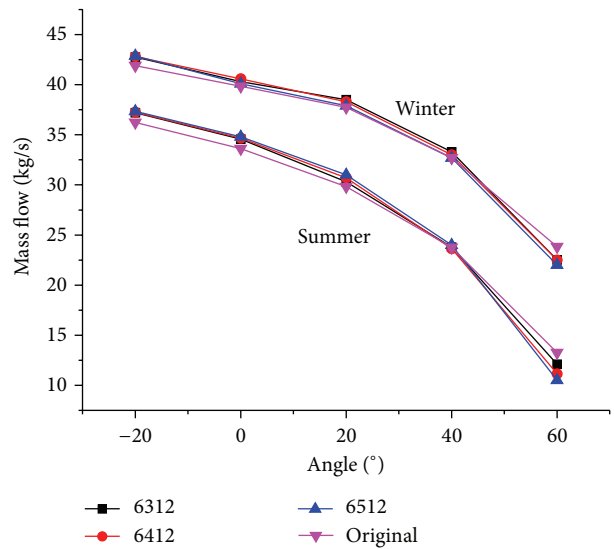
move away from the leading edge can slightly improve the guide vane flow regulating range.

Figures 17 and 18 show the velocity vector distribution of 6512 and original profile at 60° setting angle. By comparing their flow field distribution, it was found that flow separation occurred at the trailing edge of the suction side of the original guide vane. Instead, 6512 has no obvious flow separation; the flow field distribution is more uniform, reducing the flow loss of the fluid. Therefore, 6512 not only can improve the flow regulation range of the guide vane, but also can reduce the flow loss.

When the guide vane setting angle is 60 degrees, the influence of the mass flow regulation capacity of compressor is the most. Therefore, this paper will further discuss the adjustment ability of the guide vane setting angle at 60°. Table 2 shows the value of the mass flow, the mass flow change ratio, and efficiency of the original profile and 10 kinds of NACA profile at 60 degrees in summer and in winter, respectively. In the table, a negative sign on behalf of the mass flow ratio decreases, and the more it reduces, the greater the flow regulation ability is, and the less the compressed gas wasted. From the numerical value, 0008, 4412, 6412, 6408, and 6512 have better flow regulation capacity; they can expand the flow regulation range of VIGV. Among them, the mass change ratio of 6408 profile is the largest, but the efficiency of the compressor is reduced by using this kind of profile. Overall, the regulation performance of 6512 profile is the best, maximum to expand 17.45% in summer and 7.64%



(a) Profiles



(b) The change of mass flow with the setting angles

FIGURE 16: Guide vanes with different position of camber.

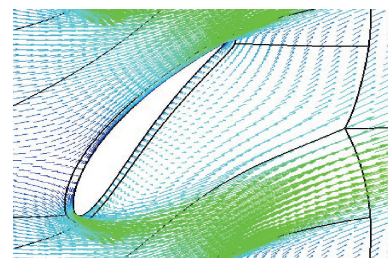


FIGURE 17: Velocity vector distribution of 6512 at 60° setting angle.

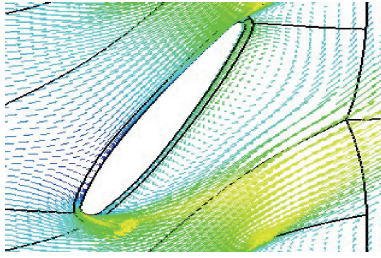


FIGURE 18: Velocity vector distribution of original profile at 60° setting angle.

in winter, and it improves the efficiency of the compressor slightly.

It can be seen from the table that the change rate of mass flow in summer is higher than that in winter. Although this is the case, the expansion of the flow regulation range of the guide vanes in winter is more significant, because the evacuation of compressed gas is usually higher in winter than that in summer due to the principle of thermal expansion and contraction. Therefore, we are more concerned about the flow regulation capacity of VIGV in winter.

5. Conclusion

The two improved channels in this paper can effectively eliminate the influence of the tip clearance on the flow regulation of VIGV. And they can improve the performance of compressor, such as reducing power and increasing efficiency. Type 2 is much better than Type 1; the maximum expansion of mass flow regulation range is 15.19% in summer and 9.16% in winter.

Reducing the guide vane thickness, increasing the guide vane camber, and increasing the distance between the maximum camber position and the leading edge of guide vane can help expand the range of mass flow regulation. Considering the performance of compressor, the best guide vane profile is NACA 6512; it can expand the range of mass flow regulation by 17.45% in summer and 7.64% in winter.

In conclusion, combined with the structure of Type 2 channel, NACA 6512 as the guide vane profile can expand the mass flow regulation range by 32.64% in summer and 16.8% in winter; at the same time the performance of the compressor is slightly increased.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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