Small centrifugal compressor performance trend prediction based on computational fluid dynamic

P A Fadilah, D F Erawan

Chroma International

Abstract. Centrifugal compressors (impeller), sometimes termed radial compressors, are a subclass of dynamic axisymmetric turbomachinery device. The idealized compressive dynamic turbo-machine achieves a pressure rise by adding kinetic energy/velocity to a continuous flow of fluid through the rotor or impeller. This kinetic energy is then converted to an increase in potential energy/static pressure by slowing the flow through a diffuser. Small Centrifugal compressor now is commonly used for mini turbojet engine which applications are in rapid drone among others. The usage of small centrifugal compressor in the mini turbojet has several advantages. One of them is that it can give higher pressure ratio than axial compressor (for example common single stage small centrifugal compressor can give 3-4 in pressure ratio at 80000-98000 rpm). The purpose of this paper is to assess the effect of geometry parameters, such as fillet radius, number of splitter and blades, to the pressure ratio. In this paper, typical small centrifugal compressor with diameter of 6.6 cm will be simulated using NUMECA, a CFD software and their results will be discussed to map the effect of each geometry parameter to pressure ratio hence compressor performance. Different geometry parameters are calculated and compared at several boundary conditions and flow setting to explore the trend of pressure ratio evolution with the change of those parameters. Based on the simulation result is indicated that there is similar effect on the applying splitter and adding blade number in the impeller configuration to increase the pressure ratio. In another case, adding fillet at the end of impeller hub wall give tendency to reduce compressor pressure ratio.

1. Introduction

Centrifugal compressor is a type of compressor with radial design. The performance of a turbomachinery device, such as centrifugal compressor is affected by external condition such as ambient pressure, ambient temperature, and the flow characteristic through in the designed device. The centrifugal compressor operates by drowning or suck air into the center of a rotating impeller with radial blades and the flow is pushed toward to the center by centrifugal force. Radial movement of the air results a pressure rise and generates kinetic energy. In the figure 1, it is illustrated the common centrifugal compressor diagram. In this study will be assessed the influence of applying fillet, splitter and number of blades to the centrifugal compressor performance.
The study from Justin Jongsik Oh [1], indicates that end wall hub fillet give tendency to decrease pressure ratio. Meanwhile, the fillet is commonly used in industrial application to reduce stress concentration at the hub blade section. Therefore in this paper, the effect of fillet radius to compressor performance will be mapped and analyzed. Another parameters which will be studied in this paper concern the splitter and number of blade in the impeller configuration. Q.H. Nagpurwala [2] stated that there are several parameters that can affect the compressor pressure ratio such as Temperature difference between inlet and outlet, heat coefficient (Cp), and slip factor. The later is affected by compressor geometry parameter such as number of blade and outlet angle of the blade (beta). Furthermore, according to the Akshay Y. [3] their study about the effect of applying splitter on the centrifugal compressor indicates that applying splitter give higher compressor pressure ratio. Another study from Ye Yuan and Shouqi Yuan [4] also indicate the similar conclusion by applying different splitter lengths.

2. Simulation Cases
There are six cases that will be simulated in this paper. For each case similar boundary condition and flow setting are applied. All calculation are done with unique RPM which is 100000. Varying parameter in the study are: number of splitter, number of blade and radius of fillet.

2.1. Centrifugal compressor with 6 blades and 6 splitter
In this case the centrifugal compressor with 6 main blades and 6 splitters will be simulated under several mass flow conditions, which is variated between 0.3 to 0.6 kg/s.

2.2. Number of blade effect
Using similar setting and boundary conditions as previous cases (in point A), the studied centrifugal compressor will be simulated in at least three blade configurations: 6 main blades, 8 blades, and 10 blades. All configuration is simulated without splitter.

2.3. Effect on Fillet Radius
In this analysis, the effect of applying fillet on the end wall hub of the centrifugal compressor is simulated. The simulation is conducted to assess how big the fillet influence on the centrifugal compressor performance reduction. There are two fillet radii that will be assessed in this study: configuration with 1 mm and 2 mm end wall fillet at the hub.

Figure 1. Centrifugal compressor stage and velocity diagram [1].
Table 1 summarizes all cases which are assessed and discussed in this paper.

**Table 1. Summary of simulated cases.**

| Case | RPM   | Mass Flow | Splitter | Blades | Fillet |
|------|-------|-----------|----------|--------|--------|
| 1    | 100000| Varied    | 6        | 6      | w/o    |
| 2    | 100000| Varied    | w/o      | 6      | w/o    |
| 3    | 100000| Varied    | w/o      | 8      | w/o    |
| 4    | 100000| Varied    | w/o      | 10     | w/o    |
| 5    | 100000| Varied    | 6        | 6      | 1 mm   |
| 6    | 100000| Varied    | 6        | 6      | 2 mm   |

3. Equations

The following are the formulas and relations that rule the relation of several thermodynamic parameters of the centrifugal compressor.

$$\sigma = \frac{C_w}{C_{w2}}$$  \hspace{1cm} (1)

$\sigma$ is the slip factor coefficient.

$$W = \psi \omega U^2$$  \hspace{1cm} (2)

Equation (2) defines the compressor required power, which power is function of slip factor and $U$, where $U$ is impeller tip speed. $\psi$ is the power input factor which represent the correction from theoretical power equation:

$$T_{03} - T_{01} = \frac{\psi \omega U^2}{c_p}$$  \hspace{1cm} (3)

$$\frac{p_{03}}{p_{01}} = \left( \frac{T_{03}}{T_{01}} \right)^{(\gamma/(\gamma-1))} = \left[ 1 + \eta_e (T_{03} - T_{01}) \right]^{(\gamma/(\gamma-1))}$$  \hspace{1cm} (4)

Equation (4) defines the relation between temperature differences and the compressor pressure ratio. The compressor pressure ratio based on the equation (4) is function of temperature difference between inlet and outlet section, compressor efficiency and heat capacity ration. Following equation (5) explains about how geometry parameter of the impeller can affect the performance on compressor assembly.

$$\sigma = \text{slip factor} = 1 - \sqrt{\frac{\cos \beta}{Z^0}}$$  \hspace{1cm} (5)

where $Z$ defines the number of impeller blade and $\beta$ denote the blade angle.

4. Computational simulations

4.1. Domain computation

The domain computation of the centrifugal compressor is generated by IGG, IGG is a part of NUMECA software. In the IGG, the CAD model is converted into .dat file. By using IGG, the computational domain of the centrifugal compressor is modeled only in “one-piece configuration” taken from the whole compressor model. The computational domain is depicted in the figure 2 and figure 3.

4.2. Meshing

For meshing the computational domain, Autogrid-5 from NUMECA is used. This structured mesh generator is completed with some workbench tools, which make the meshing process is faster with
good quality. Meshing results are depicted in the figure 4 to figure 6. Figure 4 and figure 5 show the structured mesh which is automatically generated by Autogrid-5.

**Figure 2.** Computational geometry model of impeller in the case 1 with 6 main blade and 6 splitter.

**Figure 3.** Computational Domain (consist of main blade and splitter).

**Figure 4.** Two-dimensional mesh of the blades (main blade and splitter).
In the Figure 5, is shown the meridional view of the analyzed centrifugal compressor, the flow path is illustrated by each line of the mesh. For the Figure 6, depicted the full configuration-three dimensional structured mesh of analyzed centrifugal compressor.

Figure 6. Three-dimensional mesh (main blade-splitter and fillet configuration).

4.3. Simulation condition
The simulation use Spalart Allmaras flow model in steady state simulation type. The convergence criteria uses the difference between inlet mass flow and outlet mass flow below 1 % and the residual below -6 (using NUMECA standard convergence criteria).

Similar mass flow variation are applied in all the cases from case 1 to case 6 at the 100000 rpm. In the figure 7 and figure 8 are depicted the mass flow convergence curve between inlet and outlet boundary and residual simulation convergence curve.

Figure 7. Inlet-outlet mass flow convergence curve.
5. Simulation result
The result of each case is assessed in this section. The effect of splitter, the effect of blade number and the effect of applying fillet to the compressor characteristic performance will be discussed.

5.1. Effect of splitter
In this case there are two models of the simulation, the first model is centrifugal compressor with six main blade and the another one is centrifugal compressor without splitter. The simulation result is depicted in figure 9.

![Figure 8. Residual simulation convergence curve.](image)

![Figure 9. Effect of splitter to the impeller pressure ratio.](image)

Based on the simulation result, case 1 (impeller with six main blades and six splitter) have a higher pressure ratio than impeller in case 2 (impeller configuration without splitter). Furthermore, the plots show also that the pressure ratio is decreasing when mass flow rate increase. These results are as expected by theory.

5.2. Effect on blade number
In the following cases, the effect of blade number to the compressor pressure ratio is assessed. Three configurations of blade number are calculated: six, eight and ten main blade.
Based on the simulation results, the increase of blade number of the impeller has a positive effect on pressure ratio, i.e. it increases the pressure ratio. This result is in confirmation with the Wiesner correlation, i.e. equation (3) to (5). We can also note that the increase of mass flow decreases the pressure ratio, same as the result of previous cases.

5.3. Effect of end wall fillet radius
In the last case, three different impeller model are simulated, model with no end wall fillet, model with 1 mm end wall fillet, and the last model is impeller with 2 mm fillet. The simulation result are shown in the figure 11 below.

Depend on the simulation result, ‘end wall fillet’ have relatively significant influence in the compressor pressure ratio. Greater ‘end wall fillet’ has tendency to reduce the compressor pressure ratio. The following figure 12 plots the efficiency vs mass flow for the case of fillet application. It also shows that the increase of fillet radius tend to reduce the compressor efficiency.
5.4. Pressure and velocity contour

In this section will be summarized the simulation result in the pressure contour and velocity vector of each cases.

Figure 12. Effect of fillet to the compressor efficiency.

![Figure 12. Effect of fillet to the compressor efficiency.](image)

Figure 13. Stream line visualisation through the blade.

![Figure 13. Stream line visualisation through the blade.](image)

Figure 14 show the streamline (relative velocity) throught the impeller domain. Based on the simulation result that is presented in figure 14, there are no flow separation that found in compressor with 10 main blades configuration.

![Figure 14. Effect of blade number to the velocity characteristics.](image)
Figure 14 summarizes the difference of velocity contour between case 2 until case 4. Velocity contour in the figure 14 indicates that recirculation flow or thick boundary layer (represented by blue color) is reduced when the blade number increases.

![Velocity vector](image1.png)

**Figure 14.** Velocity vector that indicate the recirculation area at the main blade of case 2 impeller.

Adding splitter in the blade configuration also have similar effect to reduce recirculation at the blade. Figure 16 shows how splitter can affect to reduce flow recirculation.

![Velocity characteristic](image2.png)

**Figure 16.** Effect of adding splitter to the velocity characteristic.

![Pressure contour](image3.png)

**Figure 17.** Effect on adding fillet to the impeller compressor ratio.

In the figure 17, the effect of adding end wall fillet in the impeller configuration is shown with pressure contour of each cases. The difference of each contour is slightly small, the void in the pressure contour is indicate that the value is greater than setted color map/legend. In the case 1 the void is a little more greated that void in the case 6, which is can be stated that the average pressure in the case 1 is higher than case 6.
6. Concluding remarks
There are several aspects that can influence centrifugal compressor/impeller pressure ratio and its efficiency such as splitter, number of impeller blade and end wall fillet. Based on our study, several points be concluded. First, the effect of adding splitter in the impeller configuration has tendency to increase pressure ratio as well as adding blade. Secondly, the fillet radius dimension affect the pressure ratio and efficiency. Since the increase of fillet radius will decrease the compressor performance, it is necessary to find an optimal radius to accommodate structural requirement. In addition to the study of compressor pressure ratio, the study of flow recirculation shows that adding number of blade and splitter has positive impact by reducing flow recirculation.

References

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