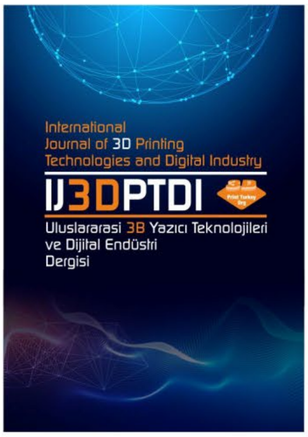

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INVESTIGATION OF STRESSES ON IMPELLER BLADES BY COMPUTATIONAL FLUID DYNAMICS (CFD) ANALYSES

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ABSTRACT

This research explores how temperature, pressure, and blade thickness influence stresses on impeller blades. During operation, the impeller is subjected to a variety of temperature, fluid, and mechanical stresses. If the tensions are too great, these may cause deformation of the impeller blades. HAUS Centrifuge Technologies supplied the impeller used in this case study, which was destroyed in the field during the 33000rpm operation. Six blade thickness offsets ranging from 0.05mm to 0.15mm were structurally examined, and the Von-Mises stresses were compared to the impeller material yield strength. Then, the impeller with the lowest stress (197.43MPa) was chosen for the Fluid-Solid Interaction (FSI) analysis. It was then manufactured, and a performance test utilizing ISO 5389 was conducted in a test facility. According to the Computational Fluid Dynamics (CFD) data, the polytropic efficiency of the thicker impeller rose to 86.57%, whereas the polytropic efficiency of the original impeller was 75.8%. With the thicker impeller, the volume flow rate reduced from 4211.3m^3/h to 3658.3m^3/h. Based on the data collected, it was determined that increasing the thickness of the blade minimizes the forces operating on the blade.

Keywords: Blade thickness, CFD, FSI, Impeller, Von-Mises stress, Polytropic efficiency.

1. INTRODUCTION

The turbo compressor shown in Figure 1 is composed of an inlet cover, an impeller, diffusers, and a volute. The inlet cover draws air in, which then flows past the impeller. In pressurizing air, the impeller is subjected to a variety of stresses. These stresses are caused by heat, fluid, and centrifugal forces. As seen in Figure 2, these stresses can distort or even fracture the impeller blades if they are excessive.

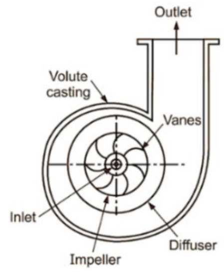


Figure 1. Compressor schematic.

The cost of manufacturing an impeller is extremely high, and a damaged impeller cannot be repaired. Therefore, the impeller's design parameters must be calculated and selected prior to production.

Figure 2. Fracture on impeller blade (HAUS Turbo blower impeller).

Computer Assisted Engineering (CAE) software's are used to study and optimize impellers to avoid the danger of producing impellers that are not optimal. By doing structural and fluid analyses on the impeller, excessive stress locations can be discovered, and the production of suboptimal impellers avoided.

Using an FSI analysis, it is possible to see the Coriolis forces and centrifugal forces generated by the impeller. An FSI analysis is a Multiphysics interaction between fluid flow and a solid structure. There are two ways to do an FSI analysis: one-way coupling and two-way coupling. Benra et al. [1] compared the one-way coupling method and the two-way coupling method. In a one-way analysis, the CFD analysis is conducted first, and the findings are then imported into the structural analysis module. In a two-way analysis, structural analysis is performed first, and the results are passed to a CFD module. The study by Gu et al. demonstrates the effect of FSI on rotational forces. The study indicated that fluid pressures significantly affect Von-Mises stress [2].

As previously stated, there are two approaches to conduct an FSI simulation. In a one-way coupling analysis, the pressure forces influence the impeller structural strength, life span and stability as established by Lee et al. [3]. Gong et al. [4] explain that in a two-way coupling analysis, the structural deformation of the impeller blades can influence the aerodynamic stresses within the impeller blades. By utilizing FSI analysis we can predict where the maximum and minimum stresses occur in the impeller and avoid the production of unoptimized impellers.

2. MATERIAL AND METHOD

This study aims to determine whether Von-Mises stresses are affected by blade thickness. This study's impeller was constructed from an aluminum alloy (AL T6 7075) with a yield strength of around 490 MPa. In this study, six distinct impeller models with differing blade thicknesses were evaluated, as indicated in Table 2. The weight of the impellers was also considered, as it affects the balance of the magnetic bearings. Six models were analyzed structurally to determine which impeller had the lowest Von-Mises stress. For comparative purposes, the original impeller and the impeller with the lowest Von-Mises stress were used for the FSI study.

Table 1 shows the mesh statistics and type used in the structural analysis study.

Table 1. Mesh data

	Original	Thickened	Type	Element size	
				Blades	**Body**
Nodes	4513053	4598844	Tetrahedral	0.4 mm	5 mm
Elements	2615108	2672961	Tetrahedral	0.4 mm	5 mm

Table 2. Impeller Blade Thickness.

Impeller blade thickness (t)		
Blade offset (mm)	**Weight gain (g)**	**Total weight (g)**
Original	-	2135.5
0.05	12.863	2148.4
0.075	20.78	2156.3
0.1	26.75	2162.3
0.125	34.82	2170.4
0.15	42.06	2177.6

The impeller provided by HAUS can operate at a maximum rotational velocity of 33000 rpm with a pressure rise of 1 bar and ambient temperature of 40 °C. These same conditions were used for the FSI analysis. In the CFD setup, a shear-stress transport (SST) turbulence model with an automatic wall function as well as heat transfer model of total energy was used as our domain boundary conditions. The analysis also had a residual target of 10^{-6}. The same boundary conditions were used for the structural analysis of the impeller (Figure 3).

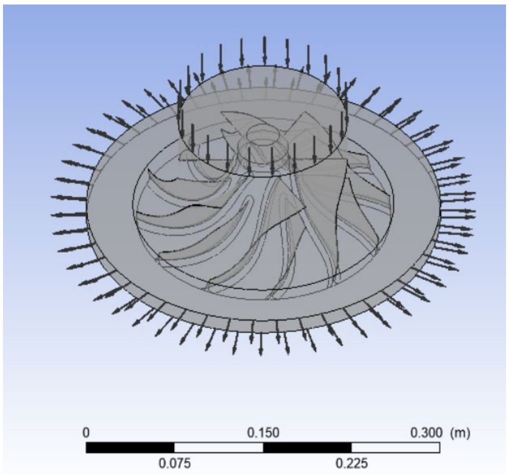


Figure 3. Impeller Fluid Domain.

3. RESULTS AND DISCUSSION

3.1. Static Structural Analysis Results

From the initial static structural analysis results, it was observed that the impellers Von-Mises stresses did not exceed the yield stress of the material. Figure 4 shows that the 0.1 mm offset has the lowest stress of 186.64MPa acting on it.

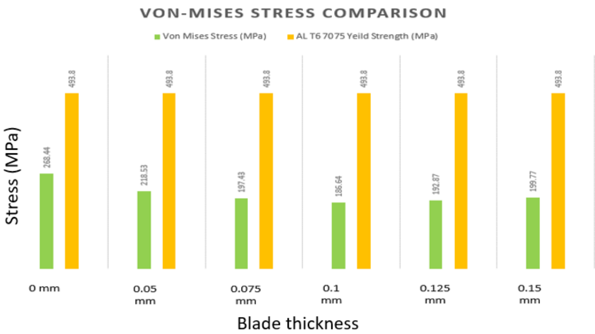


Figure 4. Von-Mises Stress Comparison of Original and Thickened Impeller.

3.2. Computational Fluid Dynamics (CFD) Analysis Results

CFD results of original and thickened impeller are presented in Table 3.

Table 2. CFD Results of Original and Thickened Impeller.

Impeller CFD Performance Results		
	Original impeller	0.1 mm offset impeller
Rotational Speed (ω)	33000 rpm	33000 rpm
Mass Flow Rate (ṁ)	1.53 kg/s	1.53 kg/s
Volume Flow Rate (Q)	4.35 m^3/s	4.32 m^3/s
Inlet Pressure (P1)	1.01 bar	1.01 bar
Discharge Pressure (P2)	2.10 bar	2.06 bar
Pressure Ratio (P2/P1)	2.08	2.04
Inlet Temperature (T1)	40.9 °C	40.2 °C
Discharge Temperature (T2)	126.9 °C	123.7 °C
Temperature Ratio (T2/T1)	3.10	3.08
Polytropic Exponent (n)	1.83	1.73
Polytropic Efficiency (ηp)	63.05%	67.54%

According to the CFD data, the polytropic efficiency (η_p) of the thicker impeller increased by 4.49% compared to the original impeller. By using the polytropic exponent n, the polytropic efficiency can be calculated. The value of the polytropic exponent n varies with the pressure ratio and temperature ratio. The formulas for these calculations were derived from ISO 5389 standards.

$$\eta_p = \frac{n(k-1)}{k(n-1)} \tag{1}$$

Where k is the isentropic exponent. The value of the isentropic exponent for ideal gases is approximately 1.4 according to the ISO 5389 standards [5].

$$n = \frac{\ln(\frac{P2}{P1})}{\ln(\frac{P2}{P1}) - \ln(\frac{T2}{T1})} \tag{2}$$

The polytropic efficiency derived from CFD studies is only applicable to the impeller and not the entire compressor stage. The thicker impeller has a lower temperature ratio than the original impeller. The reduction in discharge temperature increased the polytropic efficiency. [6, 7] Xinqian Zheng et al have demonstrated that high temperatures result in large loads on the impeller. However, it is important to note that results collected from Table 2 are only within the impeller fluid domain and not the whole compression operation.

The volume flow rate was also another important factor to note. Since the impeller blades have been thickened, it was predicted that the volume flow rate would decrease. The

CFD study results indicate a small decrease in volume flow from 4.35 m^3/s to 4.32 m^3/s. This is due to the fact that the volume flow rate is affected by the passage area between the impeller blades. By increasing the thickness of the blades, the total passage area between the blades decreases, hence reduce the volume flow rate.

The HAUS turbo blower was utilized to test the impeller's performance. Figure 5 is a schematic representation of the test bench. The turbo blower and discharge pipes were configured in accordance with ISO 5167 [8] specifications.

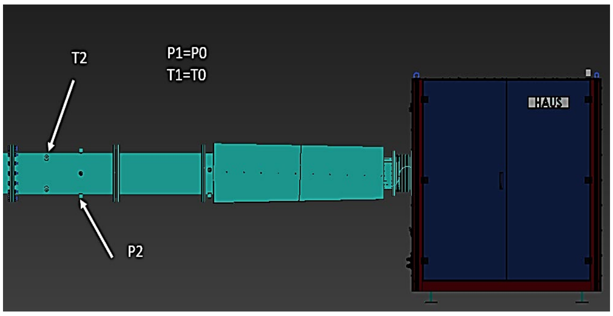


Figure 5. HAUS Turbo Blower Test Bench.

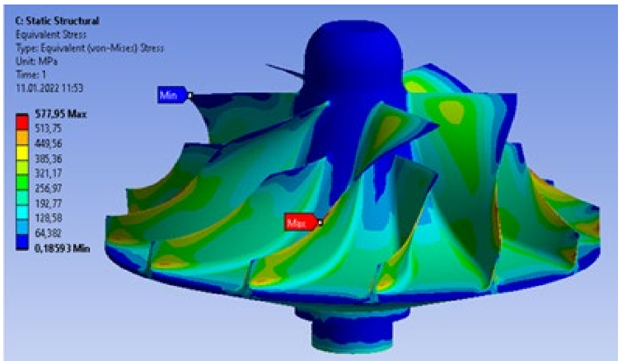
During the performance test of the impellers, a small increase in polytropic efficiency was noticed during the compression stage shown in Table 3. This slight increase is not as high as that to the CFD results. Reasons for this could be due to heat loss, friction, and ambient conditions. The volume flow rate has decreased from 1.33 m^3/s to 1.26 m^3/s. This is consistent with the CFD predictions.

Table 3. Experimental Performance Test Results of the Original and Thickened Impeller.

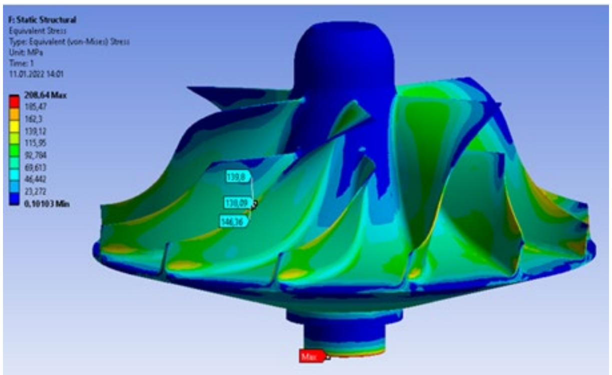
Experimental Performance Test Data Results		
	Original impeller	**0.1 mm offset impeller**
Rotational Speed (ω)	33000 rpm	33000 rpm
Mass Flow Rate ($\dot{m}$)	1.51 kg/s	1.53 kg/s
Volume Flow Rate (Q)	1.33 m^3/s	1.26 m^3/s
Inlet Pressure (P1)	1.02 bar	1.03 bar
Discharge Pressure (P2)	2.15 bar	2.11 bar
Pressure Ratio (P2/P1)	2.11	2.06
Inlet Temperature (T1)	13.9 °C	12.3 °C
Discharge Temperature (T2)	101.9 °C	96.8 °C
Temperature Ratio (T2/T1)	7.33	7.87
Polytropic Exponent (η)	1.60	1.57
Polytropic Efficiency (ηp)	79.50%	79.60%

3.3. Fluid-Solid Interaction (FSI) Results

Based on the results of the FSI, the original impeller experienced some type of deformation or fracture. Figure 6(a) shows the highest value of the Von-Mises stress on the impeller, which is 577.95 MPa. As previously stated, the yield strength of AL T6 7075 is 493 MPa. This indicates that the stress exerted on the original impeller significantly exceeds the yield stress of the material. The fracture location depicted in Figure 2 is similar to where the maximum stress point is shown in Figure 6(a). The total deformation of the original impeller shows a maximum value of 1.3mm. Since the yield stress of the material was exceeded, the blade tips will not go back to their original shape because of the plastic deformation effect.

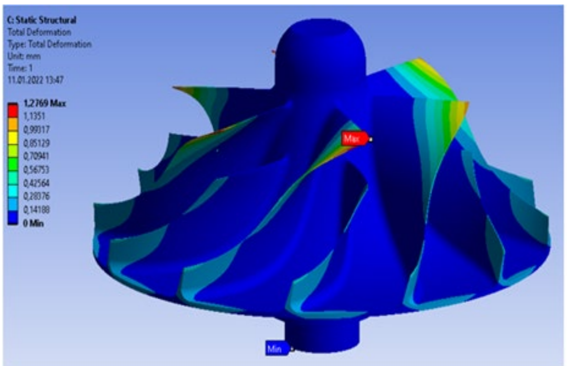


(a)

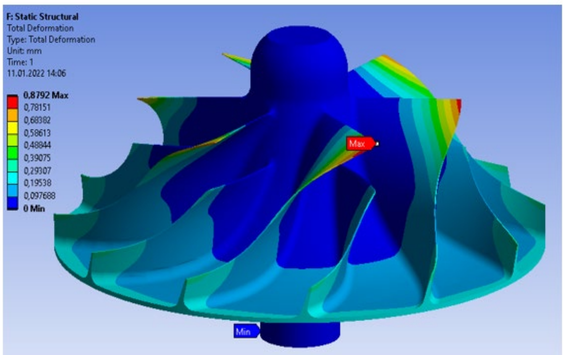


(b)
Figure 6. Von-Mises Stresses (a) Original Impeller, (b) Thickened Impeller.

The maximum Von-Mises stress exerted on the thicker impeller, on the other hand, is 208.64 MPa. This value is much lower than the yield stress of the material, which is 493 MPa. In addition, the total deformation decreases significantly from 1.3mm to 0.9mm. These results show us that the thicker impeller will experience only elastic deformation.



(a)



(b)
Figure 7. Total Deformation (a) Original Impeller, (b) Thickened Impeller.

3.4. On Site Performance Testing Results

Both impellers were produced at the HAUS facility and tested using the HAUS XMP122 turbo blower in accordance with ISO 5167 [8] specifications.

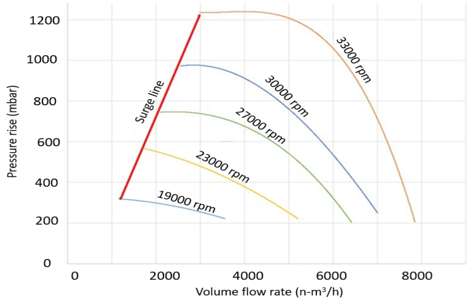


Figure 8. Experimental Performance Map of Original Impeller.

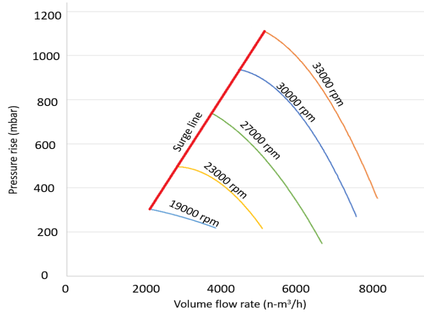


Figure 9. Experimental Performance Map of Thickened Impeller.

Performance maps were created for both impellers to identify any performance discrepancies between them. Compared to the thickened impeller, the original impeller has a slightly greater volume flow rate working range as shown in Figures 8 and 9. At 33,000 rpm, the thickened impeller cannot reach 1200 mbar before reaching the surge point, but the original impeller may run slightly above 1200 mbar before reaching the surge point. On the performance map in Figure 9, the thicker impeller's surge line has shifted to the right. This indicates that the thickened impeller will be subjected to surge events sooner than the original impeller.

4. CONCLUSION

There is an overall improvement in the structural strength of the thickened impeller. It is demonstrated that the thicker impeller can endure higher mechanical and hydrodynamic loads. However, the impeller slightly decreased the performance of the machine. Compared to the original impeller, the volume flow rate has also decreased. This is due to the smaller passage area which directly influences the volume flow rate.

According to the CFD data, the polytropic efficiency of the thickened impeller increased from 75.8% to 86.57%. The volume flow rate reduced from 4211.3 m^3/h to 3658.3 m^3/h when the thicker impeller was utilized. Based on the collected data, it was found that increasing the thickness of the blade decreases the forces operating on the blade.

In addition to a minor change in the volume flow rate, the polytropic efficiency was proven to have increased. Consequently, it can be concluded from this study that thickening the impeller had an overall favorable effect, since it can function under the same conditions as the original impeller with the minor effects on the overall performance. By applying CFD software, the time and the expenses were reduced required to produce and test the six distinct impellers. From this experimental study, the same techniques were used for the other HAUS turbo blower models and improve and optimize the service life of the impellers.

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