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Applying CFD Simulation To Analyze Turbocharger's Impeller of Marine Diesel Engines

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Abstract: Marine diesel engines use centrifugal compressors as the impeller to supercharger for diesel engines and directly driven by exhaust gas turbines. The working process of the impeller is a combination of changing parameters and thermodynamic process inside the impeller. The technical and environmental conditions of the impeller will affect to working characteristics of engine. The technology to simulate and calculate the effect of quality and gas flow learning (CFD) is developing strongly and widely applied in different fields such as: aviation, marine and industrial. Research and application of CFD simulation techniques to analyze and simulate the working process of impeller is a necessary requirement to serve the problem of operation and design of turbocharger impellers for marine ship diesel engines. In this article, the using the experimental results of the turbocharger Mitsubishi MET42SC with the DA3G impeller of the ship VTB BRAVE ship to verify the results of the impeller CFD program simulation.

Keywords: CFD, Simulation, Turbocharger, Impeller.

1. Introduction

1.1 Turbocharger's impellers for marine diesel engine.

Today's modern marine diesel engines are all equipped with turbochargers to increase the engine's power [8], [9]. Turbochargers integrated by exhaust gas turbine, air compressor, lubrication system and auxiliary equipment. It uses the exhaust gas energy of the engine to rotate the turbine that drives the impeller Figure 1a. The impeller used in turbocharger is usually a centrifugal compressor. Brands of turbochargers: MITSUBISHI, ABB, MAN, KPP, IHI, GARRET, HOLSET … usually use centrifugal compressors (Figure 1b). The advantage of this type of compressor is its compact size, suitable for the rotational speed of the turbine.

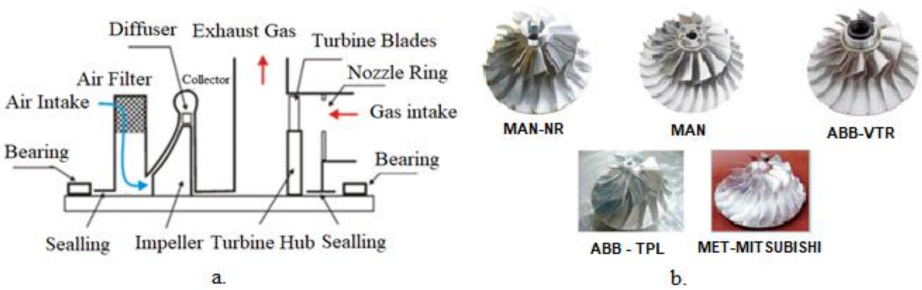

Figure 1. Centrifugal compressor construction

1.2 Increasing pressure process in turbocharger's impeller

The pressure of the pressurized air in an impeller depends on the blade profile, the ratio of the inlet diameter (Dh) and the outlet diameter (Dt) of the compressor blade [7]. For understand the operation and increase air pressure of impeller, in turn consider the principles of the processes of increasing air flow pressure in impeller described in Figure 2a.

The process of increase air pressure of impellers divided into three stages [6] as follows:

- Stage 1: The pressure of the air increased by centrifugal force or by the square of the enthalpy:

$$\Delta p_1 = u_2^2 - u_1^2 \tag{1}$$

- Stage 2: The air flow pressure increases due to a decrease in the velocity w in the impeller due to an increase in the airflow cross section:

$$\Delta p_2 = \omega_2^2 - \omega_1^2 \tag{2}$$

- Stage 3: Air pressure flow increased by the diffuser on the compressor outlet:

$$\Delta p_3 = c_2^2 - c_3^2 \tag{3}$$

The total pressure increases in an impeller can described as the following equation (4):

$$\Delta p_{tot} = (u_2^2 - u_1^2) + (w_1^2 - w_2^2) + (c_2^2 - c_3^2) \tag{4}$$

Concerning the additional pressure increase in the centrifugal field, impeller predetermined for a high-pressure ratio in an impeller frequency corresponding to a low flow ratio. It is very convenient to design exhaust turbochargers for diesel engines with only one impeller.

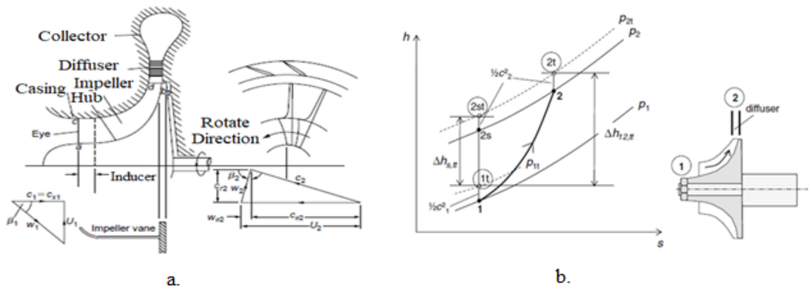

Figure 2. Increasing air flow pressure in impeller.

The process of pressurizing on the impeller is described on the h-s graph [3] in Figure 2b, in which the pressure increase stage in the compressor impeller is stage 1 - 2, here will sum up both stage 1 and 2, stage 3 is performed on the diffuser in the compressor housing, applied CFD to analyses the processes as well as the changes in the working parameters of the turbocharger according to the three processes above.

1.3 Determination actual air mass flow supplied to diesel engine

According to ship diesel engine theory, to determine the actual amount of air to ignite the amount of fuel injected into the engine cylinder [5] is determined by the following formula:

$$G_{kktt} = \frac{\pi D^2 S \eta_n \rho_k \varphi_a}{4} \tag{5}$$

Where: D cylinder diameter, S piston stroke, η_n intake coefficient of air; φ_a is the sweep coefficient, ρ_{kk} the density of the intake air and the engine.

Otherwise, to determine the actual amount of air supplied to the engine according to the air residue factor α, according to the formula:

$$G_{kktt} = \alpha.\ G_{lt} \tag{6}$$

The theoretical, amount of air [kg/ct] to ignite the amount of fuel injected into the cylinder during a g_{ct} cycle is determined:

$$G_{lt} = g_{ct.}\ G_o \tag{7}$$

With G_o theoretical amount of air to burn 1 kilogram of fuel [kg]; g_{ct} the amount of fuel injected into the engine cylinder in one cycle:

$$g_{ct} = \frac{G_{nl}}{60.i.\tau.n} \tag{8}$$

With G_{nl}: Fuel consumption for the engine in 1 hour [Kg/h], i: is the number of cylinders, τ number of strokes, n: engine revolutions [RPM].

According to (6), (7), (8) and engine parameters, choosing a suitable air residue coefficient α for 2-stroke engines, determine G_{kklt}: to burn the amount of fuel supplied to the engine.

Otherwise, according to [4], the actual air consumption to burn 1 kilogram of fuel for diesel engines is determined by the following empirical formulas:

- For diesel engines 4 strokes: G_{kktt} = 3 x 14 = 42 kgkk/ kgnl (9)

- For diesel engines 2 strokes: $G_{kktt} = 3 \times 16.5 = 51.5$ kgkk/ kgnl (10)

2. CFD simulation program of turbocharger's impeller.

2.1 Building program to simulate turbocharger impeller using CFD.

The CFD simulation program in Ansys 2020 R2 academic version [1] for impeller blades used in turbochargers conducted according to the following steps:

- Open the Workbench screen in Ansys, save the program name: "MET42SC DA3G".
- Use the CCD tool to design the compressor according to the basic parameters of the compressor such as: inlet diameter (D_h), outlet diameter (D_t), Pressure ratio (R_p), number of impeller blades (Z), Rotation of impeller N(RPM) etc…
- Then forward the impeller's data to BladesGen tool to edit the blade inlet and outlet angle, blade profile accordingly.
- Use Turbogrid to mesh the compressor blades in accordance with the simulation program,
- Transmit the data after meshing to the CFX window to run the setting of working parameters and then run the simulation program, we will receive impeller output the simulation results.

2.2 CFD Simulation running and results

We will obtain the results of air flow changes such as pressure, temperature, velocity, entropy. The results of the program obtained as follows:

1. The basic parameters describing the operation of the compressor as per Table 1 as below:

Table 1. Impeller performance results table.

Parameters	Value	Unit
Rotation Speed	-2303.83	[radian s^-1]
Inlet Mass Flow Rate	11.0690	[kg s^-1]
Inlet Volume Flow Rate	4.8659	[m^3 s^-1]
Reference Radius	0.2230	[m]
Input Power	119,664	[W]
Total Pressure Ratio	2.6103	
Total Temperature Ratio	1.3470	
Polytropic Head	1,039,460	[J kg^-1]

2. 3D simulation of the shape, size, structure of the compressor (Fig 3a.), the cross-sectional section along the direction of air flow from inlet to out of the compressor impeller (Fig 3b.) and blades mesh (Fig 3c.).

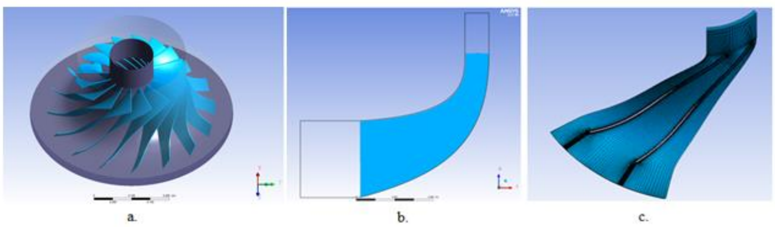

Figure 3. 3D simulation and impeller longitudinal section

3. Evolution of pressure change around impeller vane (Fig. 4a.), static and total pressure in the flow direction on a blade span from inlet to outlet of the impeller blades (Fig. 4b) and temperature change (Fig. 4c.).

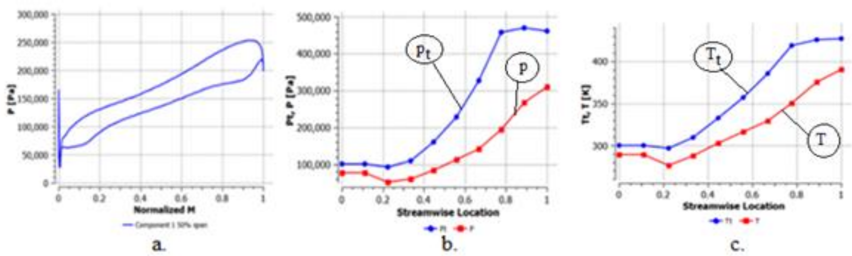

Figure 4. Pressure variation in front and behind and along the blade length.

4. The results of graphical simulation of the change of the velocity vector, the entropy of the gas flow on the blade and changing pressure of the air flow from the inlet to the outlet of the impeller graphically.
5. Graphic description the air pressure at the air inlet and outlet of the impeller vane.
6. The velocity vector represents the direction and intensity of the air flow in the.

3. Simulating impeller of Mitsubishi MET42SC – DA3G.

As analysis of the results obtained in the previous section related to the important parameters is evaluated during the working process of the impeller, in this section, the results obtained from experiment of the impeller MET42SC – DA3G of Mitsubishi will be evaluated air increase rate of impeller by CFD simulating of the impeller.

3.1 Experimental parameters of DA3G impeller.

According to the experimental results recorded on the engine fitted with DA3G impeller when testing with actual engine at the workshop [2], the working parameters related to the recorded impeller including impeller rotation N, air pressure outlet P_{rtd}, air pressure inlet P_{vtd} and fuel consumption of the engine in hour G (kg/h).

To evaluate and verify the simulation results, the tested results of the MET42SC turbocharger with Mitsubishi's DA3G impeller used on the main engine of the VTB BRAVE ship (renamed from M/V SUN FRONTIER), building at the MIURA Shipbuilding Co., Ltd in 1997.

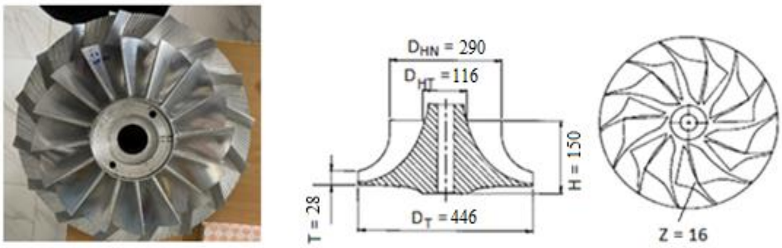

Figure 5. Drawing of DA3G impeller.

The main engine is a 2-stroke diesel engine Mitsubishi model: 6UEC33LSII, continuous power: 3927 PS and maximum power: 4400 PS; Engine Speed: 210 RPM. [2]. Mitsubishi's DA3G impeller (Figure 7) is a single-stage compressor installed on the MET42SC turbocharger. During the maintenance of the turbocharger for M/V VTB Brave, we have been opened and measuring the geometrical dimensions of impeller as shown in Table 2.

Table 2. DA3G Impeller geometry parameters.

Parameters	Value	Unit
Number of Blades Z	16	Pcs
Outlet Diameter D_T	446	mm
Shroud inlet Diameter D_{HN}	290	mm
Hub inlet Diameter D_{HT}	116	mm
High of impeller H	150	mm
Hight of Tip T	28	mm
Average of blades thick T_c	20	mm
Air of Hub inlet angle β_{1H}	40	Degree
Air of shroud inlet angle β_{1T}	65	Degree
Outlet of Hub Angle β_{2H}	22.5	Degree
Outlet of shroud Angle β_{2T}	30	Degree

Besides the geometrical dimensions, the operation environment of the impeller also an important factor that determines the operation characteristics. It is the ambient temperature and pressure of the air.

According to the results obtained in Table 2, the experimental parameters related to the working characteristics of the impeller are evaluated through the following parameters: rotation, pressure, inlet temperature and outlet temperature. The measured values are by ship testing in the condition of newly installed equipment, ensuring the allowable reliability to evaluate the working characteristics of the impeller. Experimental operation Parameters of impeller and diesel engine in M.V VTB Brave as per table 3 below:

Table 3. Experimental working parameters of impeller DA3G.

Parameters	Value			
N [V/P]	12,000	17,300	20,500	21,800
L %	50	75	100	110
P [ps]	1,954	2,931	3,927	4,210
$P_{vtđ}$ [Pa]	101,019	100,804	100,764	100,627
$P_{rtđ}$ [kg/cm^2]	0.5	1.2	1.8	2.1
$P_{rtđ}$ [Pa]	150,358	219,004	277,845	307,264
$T_{vkkđ}$ [^{o}K]	307	308	309	310
$T_{rkkđ}$ [^{o}K]	353	399	431	449
G_{nl} [kg/h]	256.7	375.9	497.6	611.1
G_{kktt} [kg/s]	3.6722	5.3703	7.1184	8.7421

3.2 Simulation with Ansys CFD.

3.2.1 Simulation conditions:

Choosing the simulation model according to the following initial conditions as below:

- The pressure of the air supplied to impeller as atmospheric pressure relative to sea level P_{vt} = 101325 Pa.
- Average ambient temperature of the air entering the impeller in the tropical area T_{vkk} = 310^{o}K (37^{o}C).
- The air consumption with the simulated values at 50%, 75%, 100 % and 110% of the engine load.
- Actual amount of air supplied to the engine [kg/s]. It is needs to determine the actual amount of air supplied through experimental and theoretical values.
- Air mass flow supplied to the engine. Using the experimental formula (10) updated in Table 4,

3.2.2 Ansys CFD simulation results.

According to the actual parameters of the DA3G impeller, Run program according to tested RPM: 12,000; 17,300; 20,500 and 21,800. The input parameters of the impeller, we have P_{vtm} =101,325 Pa; T_{kkm} =310^{o}K, actual amount of air consumed by the engine [kg/s] corresponding to each working mode of the impeller from table 3. The results obtained from the simulation for the values of P_{rtm} and T_{rkkm} record at table 4.

Table 4. Impeller working parameters from CFD simulation program

Parameters	Value			
N (V/P)	12,000	17,300	20,500	21,800
P_{vtm} [Pa]	101,325	101,325	101,325	101,325
T_{vkkm} [^{o}K]	310	310	310	310
G_{kktt} [kg/s]	3.6722	5.3703	7.1184	8.7421
P_{rtm} [Pa]	156,253	226,428	280,354	310,257
T_{rkkm} [^{o}K]	371	426	464	467

3.3 Evaluation of simulation results

According to the results in table 3 and table 5, summarizing the pressure change and outlet temperature of the impeller in the experimental state and the simulated state, we obtain the results are compared with Table 5.

Table 5. Evaluation of results

Parameters	Value			
N [RPM]	12,000	17,300	20,500	21,800
$P_{rtđ}$ [Pa]	150,358	219,004	277,845	307,264
P_{rtm} [Pa]	156,253	226,428	280,354	310,257
ΔP_r [Pa]	5,895	10,573	2,509	2,993
ΔP_r %	3.92	4.83	0.90	0.96
$T_{rkkđ}$ [^{o}K]	358	410	443	449
T_{rkkm} [^{o}K]	371	426	464	467
ΔT_{rkk} [^{o}K]	13	16	21	18
ΔT_{rkk} %	3.50	3.76	4.53	3.85

From table 5, We are obtaining a graph comparing experimental and simulation results for temperature and pressure in Figure 6. We will have working characteristics of the impeller as below:

- The law of changing pressure and temperature of the air coming out of the impeller in experimental and simulated modes is the same.

- Output pressure values of the two modes are similar and within the allowable error range ΔP_r and $\Delta P_r\%$. The biggest error lies in the rotation value of 17,300 RPM with $\Delta P_r\% = 4.83\%$

- The temperature value of the air coming out of the impeller in the two states is similar and has the largest error $\Delta t = 4.53\%$ at the rotation value of 20,500 RPM. This error is within the allowable error of the measurement, so the experimental and simulation results are similar.

- The obtained simulation results of the program are consistent with the actual working characteristics of turbocharger impeller on diesel engines.

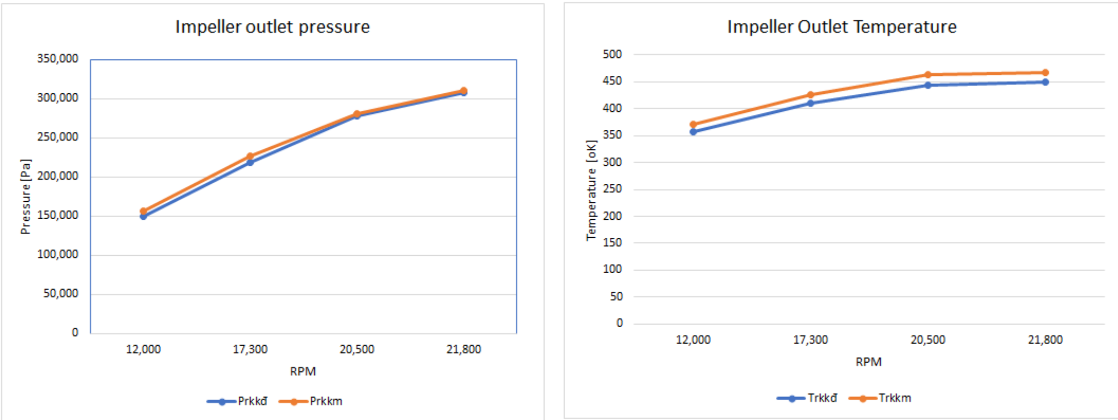

Figure 6. Comparison chart of simulation and experimental pressure and temperature comparison chart.

4. Conclusions.

The turbocharger's impeller CFD simulation program has been realistically testes according to the pressure, temperature, and air flow to evaluate the working characteristics of the impeller for the diesel engine.

This program also used as a tool to analyze the working process and design turbocharger impellers for marine diesel engines and using to develop other research related to air centrifugal compressors and turbochargers of marine diesel engines.

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