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CFD Study of Boss Fins' Effect on Performance of Marine Propellers

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***Abstract* -** With the advancing development and progressing economy, reduction in fuel consumption has proven to be a primary concern for the marine industry. This study deals with enhancing the efficiency of ship propulsion systems by reducing vortex-related losses downstream of the propeller. The method introduces a set of fins downstream the propeller placed at strategic locations pertaining to the flow field in order to reduce the vortex intensity behind and thus enhance the thrust generated. These are generally termed PBCF (propeller boss cap fins) due to the several designs having the boss cap downstream to the propeller, however, this may vary as per the ship/propeller design. For simplicity, we will refer to the boss fins as PBCF. The retro fitment of PBCF for a ship propeller is validated and the results are elaborated. Literature has been studied for past experiments for analysis of the potential of PBCF (Propeller boss cap fins) as an effective and potential energy saving device. The initial part of the paper presents the overall process of establishing an ANSYS CFX based CFD model for the standard Potsdam Propeller Test Case (PPTC) and the model's validation using the available experimental open water test results. The paper also presents a strategic design for fins for the PPTC propeller and a deep analysis of its effect on propeller performance, primarily the thrust generated and efficiency at similar operating torques. The paper also presents a study of the obtained results for pressure and velocity fields with and without PBCF for the PPTC propeller and their correlation with the overall effect on efficiency and fuel consumption.

***Keywords*:** CFD, Fluid Flow, Marine Propeller, PBCF

1. Introduction

Economic pressure and guiding requirements for enhancing the efficiency and reducing environmental harm at the same time has gained interest to improve ship propulsion productivity. Suitable ESDs (Energy saving devices) have been built-in 2000 vessels like VLCC, containers, ferries etc. The benefits of PBCF are simple structure, easy fitting, low upkeep, less investment, less demanding arrangement consent and enhancement of the propeller thrust and efficiency. The subject of how to evaluate superlatively the retrofit energy saving devices at full scale is of great interest. The consumption of energy by ship is based on different components of ship hydrodynamics system which consists of hull resistance, propulsion efficiency and hull propeller interaction [2]. The performance of a propeller is stated in terms of its open water and after hull properties. The designs of propellers are studied by evaluating their thrust (T) and torque (Q) factors, which are non-dimensionalised into thrust (K_t) and torque, (K_q) coefficients respectively, and further used to calculate the efficiency of propulsion (η) [2].

$$K_T = \frac{T}{\rho n^2 D^4} \tag{1}$$

$$K_Q = \frac{Q}{\rho n^2 D^5} \tag{2}$$

$$J = \frac{V_A}{nD} \tag{3}$$

$$\eta = \frac{JK_T}{2\pi K_Q} \tag{4}$$

Wherein D represents diameter of propeller, ρ depicts the water density, V_A represents advanced velocity while n is the notation for rotations per second. The thrust as well as torque coefficients can be represented for a series of advance coefficients (J). Open water propeller curves are quite relevant for the simulations of the uniform flow which explains that the propeller is immersed and revolved in a remote water environment with continuous constant flow of velocity V_A [2].

2. Methodology

The following subsections describe the overall methodology including the choice of PPTC propeller from SVA Potsdam, the use of its open water test results to validate the ANSYS CFX model being used, the mesh generation techniques and their utility in analysis, as well as a design of PBCF for the PPTC propeller. We also mention about numerical techniques used by the CFX solver.

2.1. PPTC propeller and Open Water Test

With the help of model scale, controllable pitch propeller in the pool test formation validation studies were conducted by SVA [19]. SVA explains the experimental open water test results which allows us to compare and validate the simulation model. The design factors considered for Potsdam propeller test case. (PPTC) propeller is shown in Table 1.

Table 1. Parameters of PPTC propeller [2]

	Notation	**Value**
Diameter (m)	*D*	0.250
Pitch Ratio	*0.7 P/D*	1.635
Area Ratio	*AE /AO*	0.779
Chord Length (m)	*0.7C*	0.104
Hub Ratio	D_h/D	0.300
No. of Blades	*Z*	5
Skew (deg)	θ	18.837
Revolutions/sec (rps)	*n*	15

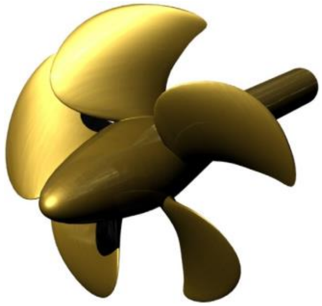


Fig 1. PPTC propeller [2]

The available experimental results for the Open Water Test performed on the PPTC propeller [2] have been taken as primary results for validation of the CFD model in use. As will be discussed in the further subsections (2.3), appropriate agreement was achieved between the simulated and experimental open water test results to validate the results and conclusions drawn using the CFD model in use, especially the results reflecting the effect of the installation of boss fins downstream the PPTC propeller. The actual experimental conditions were closely developed to simulate the open water test of PPTC. The solver used for the analysis is ANSYS CFX. The solver uses the vertex-centered method, more precisely dual-median method as the finite volume method for discretisation.

2.2. Mesh Generation

Several iterative studies based on mesh metrics like Aspect ratio, Jacobian ratio and skewness were performed to generate an appropriate mesh for the CFD model using the patch conforming method. Tetrahedral elements were generated.

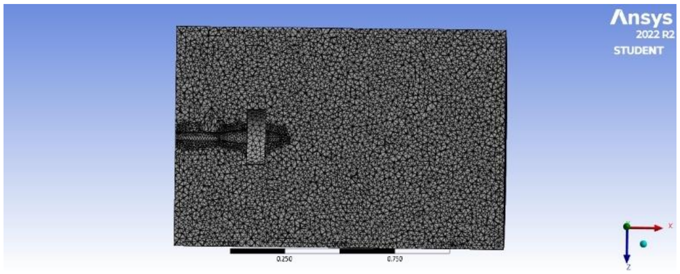


Fig 2. Non rotating zone mesh

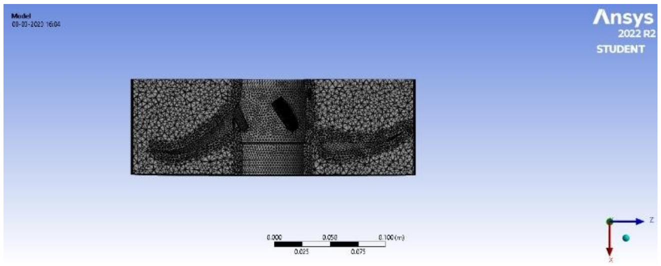


Fig 3. Rotating zone mesh

Further, appropriate zones were generated in order to accommodate the rotating and non-rotating domains of the fluid zone separately with different physical conditions. Fig 2. And Fig 3. shows the cut section of the mesh generated for the non-rotating and the rotating domain, respectively. During the flow analysis, the rotating domain's mesh is assigned rotating mesh properties with the same angular velocity as the propeller to capture the rotating effect of the propeller at a particular angular velocity. The rotating domain mesh contained 686,279 elements and 130,190 nodes, while the coarser non-rotating domain mesh contained 658,613 elements and 116,676 nodes.

2.3. Validation

[a1]The mesh was transferred to the CFX setup, where appropriate boundary conditions and flow variables were for the analysis. As per the available open water test results, the analysis was performed for a constant angular speed of 15 rotations per second for varying advance coefficients J = 0.6, 0.8, 1, 1.2, and 1.4. Fig 4. shows the boundary conditions' [a2]representation for the developed setup, and Fig 5. shows the streamlines of the resulting simulated flow. SST k-w model was used to model the flow characteristics near as well as away from the wall surface accurately.

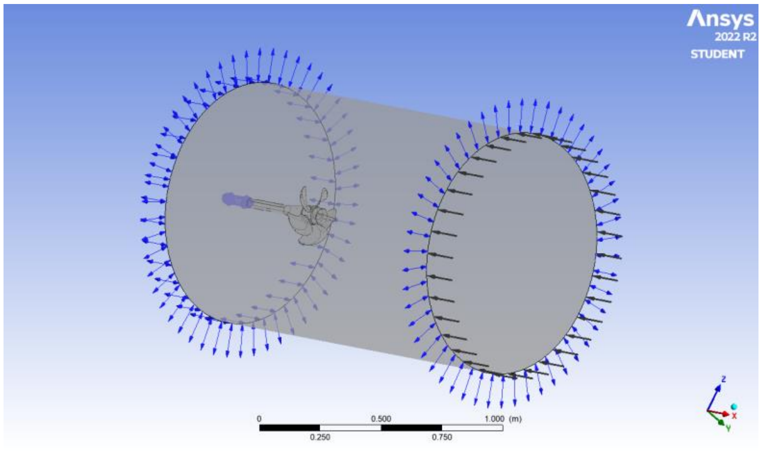


Fig 4. Boundary Conditions for CFX Setup

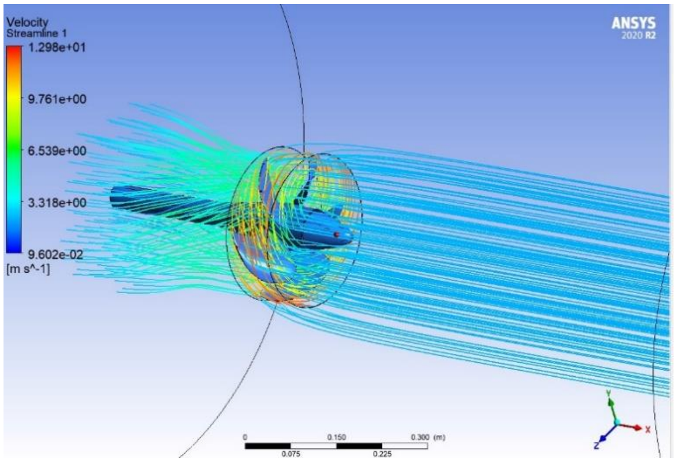


Fig 5. Depiction of resulting streamlines

The results obtained have been presented in table 2 below. Fig 6. Shows the graphical comparison of the results obtained with the experimental open water test results. As can be observed, the obtained values for the thrust and torque coefficients as well as the efficiency diligently follows the trend as well as closely matches the experimental open water test results. This proves the validity of the model for analysing the PPTC and similar marine propellers and this validation will allow us to draw important conclusions once we install PBCF on PPTC and analyse the effect on its performance. In the next section (2.4), a design for the fins for PPTC propellers has been developed and presented.

Table 2. Validation results of PPTC Propeller

Angular velocity	Advance Coeff. (J)	Thrust	Thrust Coefficient		Error in K_t (%)	Torque	Torque coefficient		Error in K_q (%)	η		Error in η (%)
(rev/s)		(N)	Calc K_t	Expt K_t		(Nm)	Calc K_q	Expt K_q		Calc η	Expt η	
15	0.6	508.14	0.5782	0.6288	8.06	29.815	0.13569	0.13964	2.83	0.407	0.430	5.38
15	0.8	434.22	0.4941	0.5100	3.13	25.207	0.11472	0.11780	2.61	0.548	0.551	0.53
15	1.0	360.58	0.4103	0.3994	2.72	20.999	0.09557	0.09749	1.97	0.683	0.652	4.78
15	1.2	273.2	0.3108	0.2949	5.41	17.756	0.08081	0.07760	4.14	0.735	0.726	1.22
15	1.4	176.12	0.2004	0.1878	6.7	12.713	0.05786	0.05588	3.54	0.772	0.749	3.05

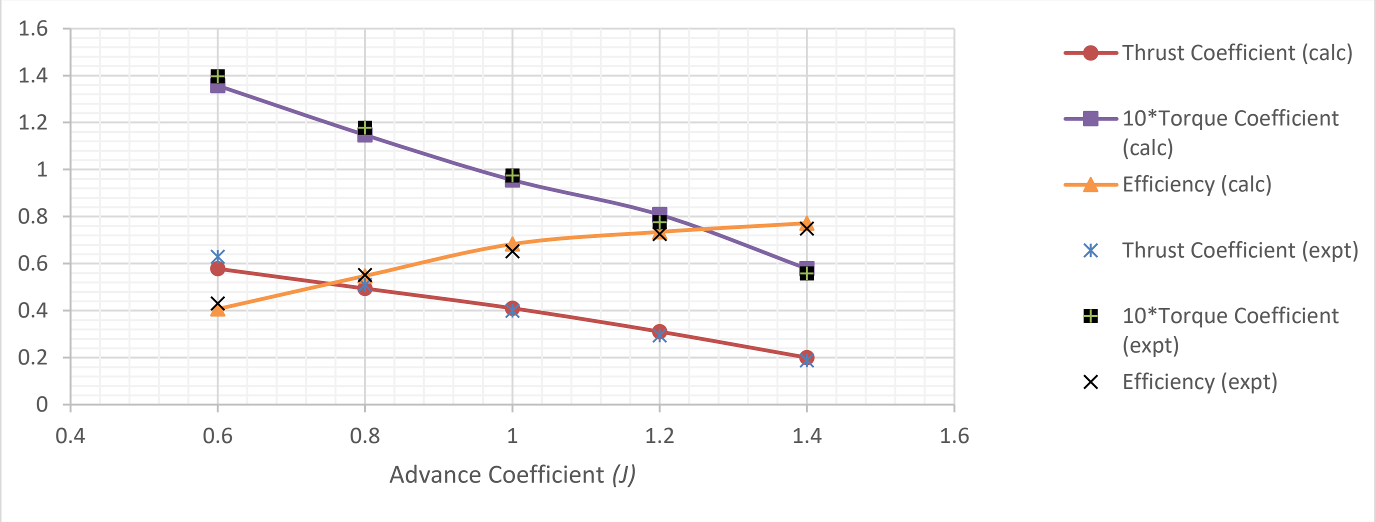


Fig 6. Graphical Representation of achieved validation using Open Water results

2.4. Design and Installation of Fins

To reduce the overall vortices and thus the drag development, it has been proposed that the fins should be placed along the pressure contour lines downstream the propeller. The contour lines were identified and the fins were designed using preliminary analysis available in the literature about fin parameters like fin angle, height and shape after a few iterative cycles to achieve a better design. Figs. 7, 8, and 9. represent the design developed for the fins and integrated with the already existing PPTC propeller.

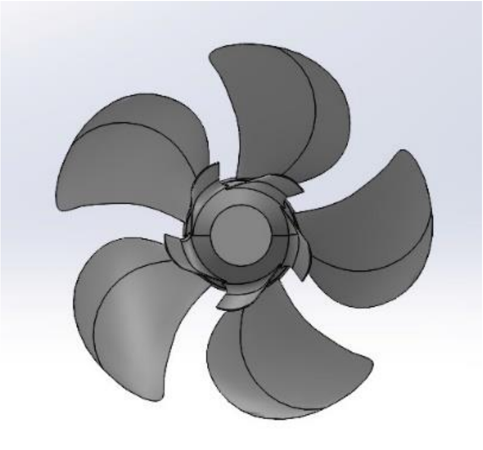


Fig 7. Front View

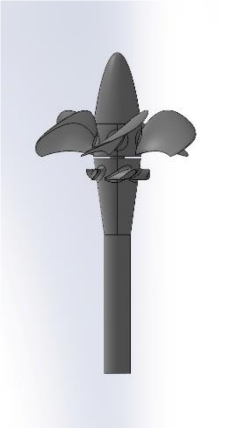


Fig 8. Side View

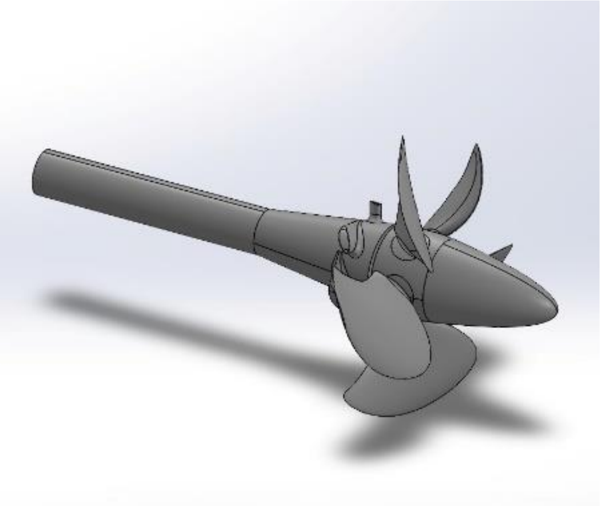


Fig 9. Isometric View

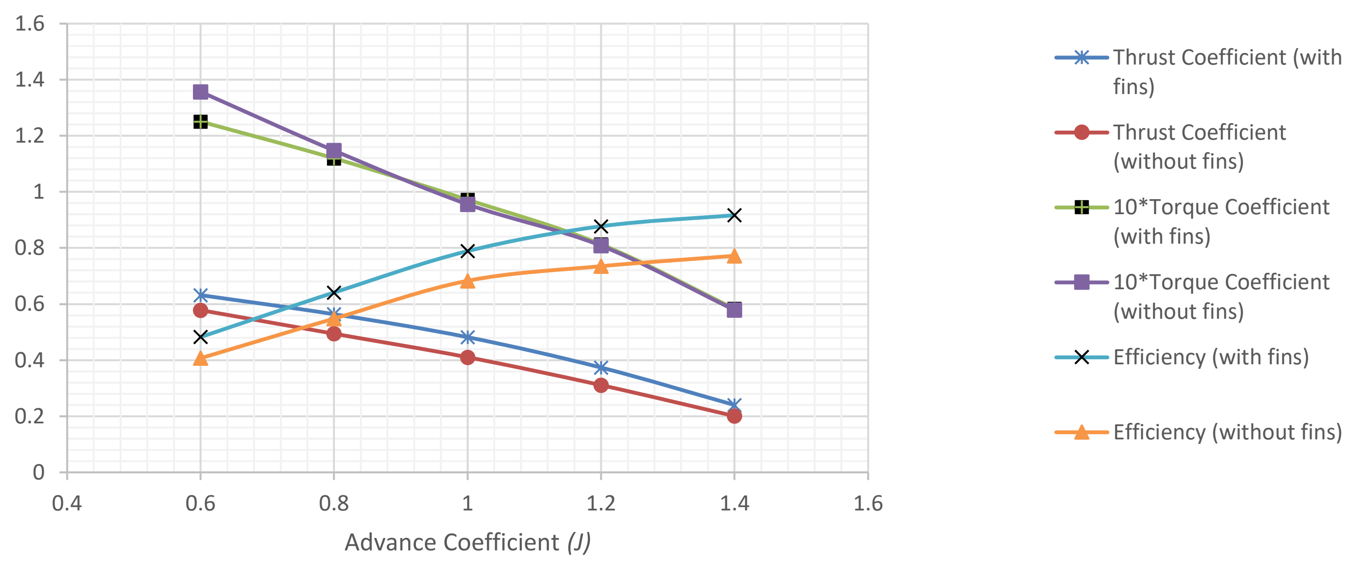
We analysed the PBCF-equipped PPTC propeller for the same flow conditions with our validated model and compared the results with the results for a normal PPTC propeller generated by the model. From the mesh generation perspective, there are now two rotating zones (PBCF and propeller). Further, it should be observed that the curvature of PBCF designed is opposite to the curvature of propeller in order to cancel out the high vorticity generated in the flow by the propeller and thus reduce the energy carried by the fluid downstream. The next section displays and discusses the obtained results for the PBCF-equipped PPTC propeller.

3. Results and Discussion

When analysed for the same flow conditions as the normal PPTC propeller, the PBCF-equipped PPTC propeller gave the following results (Table 3). Fig 10. shows the graphical representation of this comparative study.

Table 3. Comparison of Propeller Performance with and without PBCF

Angular velocity (rev/s)	Advance Coeff. (J)	Thrust (with fins) (N)	Thrust Coefficient (K_t)		Increase in K_t (%)	Torque (Nm)		Efficiency (η)		Increase in efficiency (%)
			With fins	Without fins		With fins	Without fins	With fins	Without fins	
15	0.6	555.336	0.6318	0.5782	9.27	27.483	29.815	0.4824	0.407	18.55
15	0.8	495.48	0.5637	0.4941	14.09	24.601	25.207	0.6411	0.548	16.93
15	1.0	423.463	0.4818	0.4103	17.43	21.357	20.999	0.7889	0.683	15.47
15	1.2	328.242	0.3735	0.3108	20.17	17.863	17.756	0.8774	0.735	19.44
15	1.4	210.876	0.2399	0.2004	19.71	12.811	12.713	0.9169	0.772	18.82



[a3]

Fig 10. Graphical Comparative Analysis of Propeller Performance with and without PBCF

As observed from the results obtained above, the installation of the proposed fins on the standard PPTC propeller increases the propulsive efficiency by around 15-19%. We can observe that the operating torque with and without PBCF is almost the same for any given advance coefficient, the small fluctuations in which can be attributed to system errors. The increase in the thrust is also significant ranging from 9% at lower advance coefficients (J=0.6) to a significantly larger 20% at higher advance coefficients (J=1.4). This significant increase in the thrust and efficiency of the propeller can directly be mapped with the reduced vortices downstream the propeller due to the installation of fins. However, this analysis does not take into account the effect of hull resistance or cavitation effects, which is the future scope of this work and can bring down this effect to around 10% increase in efficiency.

Several other parameters were examined to consolidate the conclusions drawn and to observe the changes in the behaviour around the propulsion system due to the installation of fins. Fig 11. and Fig 12. show the study of flow and the pressure field just around the fins. We can observe a clear demarcation between the low pressure and high pressure zones in the contour diagram indicating the flow circulation around fins and additional force components due to fins. The flow profile over the PBCF clearly explains that the thrust produced by PBCF is in the same direction as of the propeller. Fig 13. and Fig 14. show a comparative analysis of the velocity field in the fluid domain around the propulsion system with and without fins respectively. It can be clearly observed that the disturbance in the velocity field is much smaller with fins, indicating lower strength of downstream vortices and disturbances. Fig 15. and Fig 16. show a comparative analysis of the total pressure field with and without fins respectively. The fluid domain carrying a larger total pressure significantly drops with the installation of fins, a testimony to the fact that the downstream fluid with fins installed with the propeller carries much less energy than the downstream fluid of the normal propeller. The energy carried by the downstream fluid is simply in an inverse relation with the thrust generated and in a direct relation with the drag caused. This analysis clearly verifies that there is wake reduction due to installation of PBCF on propeller which enhances its working efficiency.

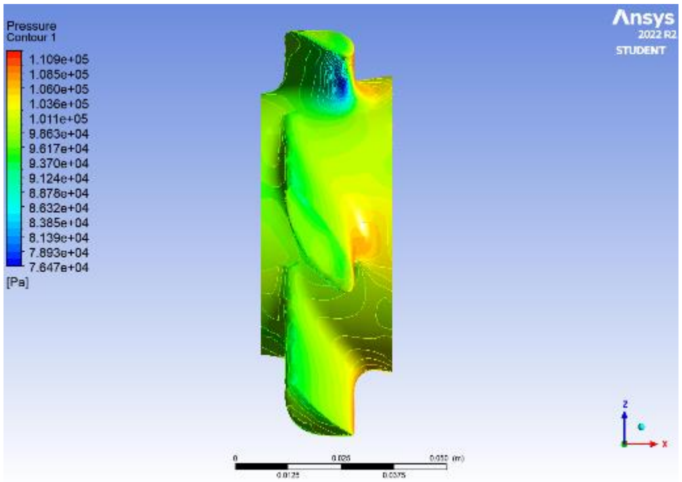


Fig 11. Flow over Fins - Pressure Contours Side View

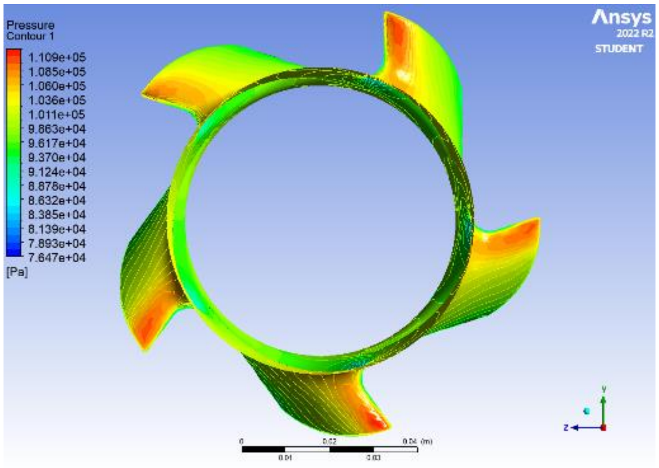


Fig 12. Flow over Fins – Pressure Contours Front View

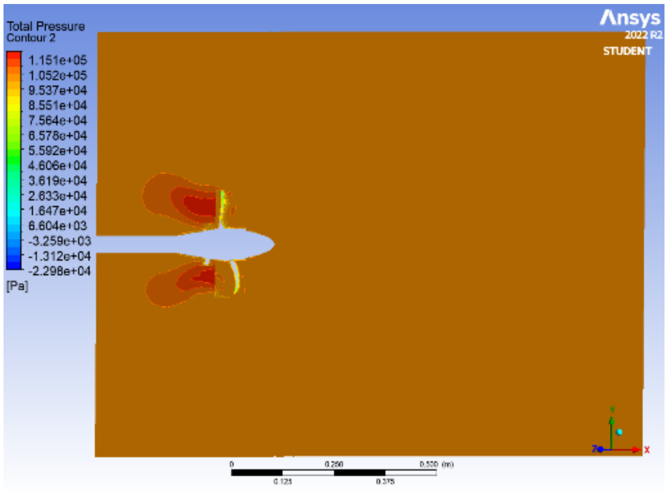


Fig 13. Total Pressure field with PBCF

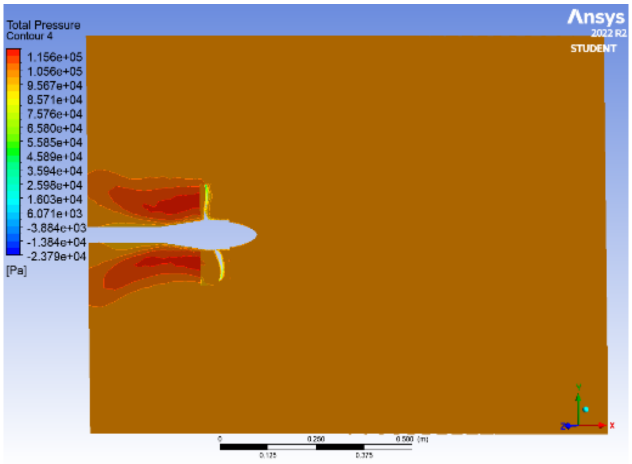


Fig 14. Total Pressure field without PBCF

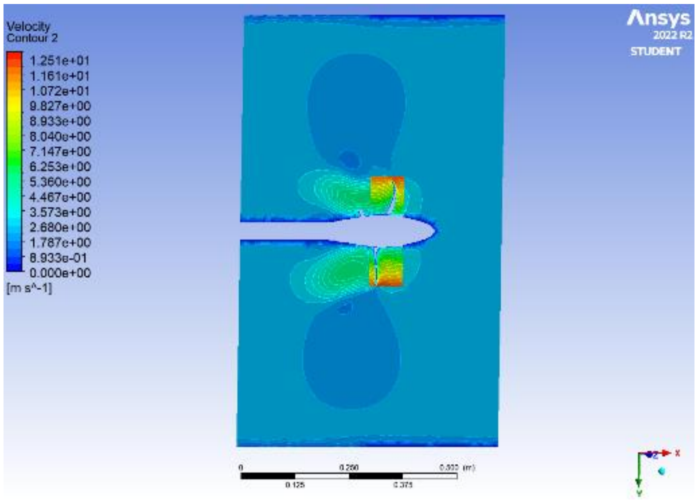


Fig 15. Velocity field with PBCF

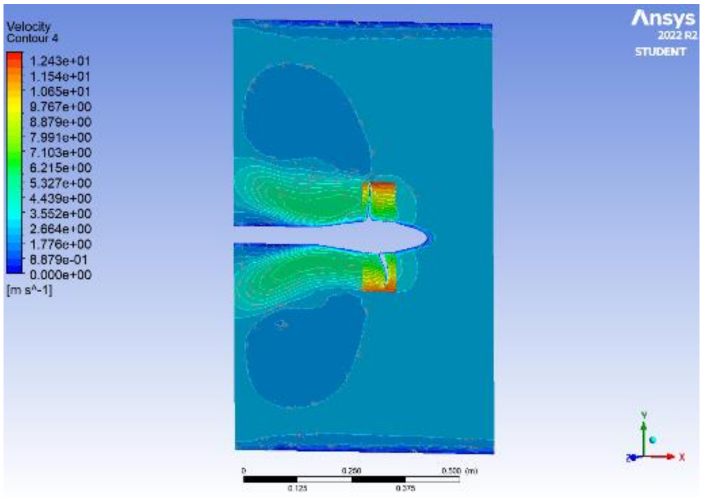


Fig 16. Velocity field without PBCF

4. Conclusion

The present study of the effect of fins on the performance of the standard PPTC propeller has led to several basic conclusions and understandings about the flow pattern behaviour, pressure fields and in general, the overall performance specifically the thrust and efficiency of the propulsion system. The design proposed for the fins using preliminary understanding of fin behaviour has led to quite good results and in turn, has provided good insights in the form of required flow patterns for an effective fin design in future. The numerical methods used and specifically the mesh strategy of including rotating zones has proven to be very effective evident from the accuracy of the results as compared to the experimental validation data. Results presented above can further be extended and developed into a methodology for designing fins for any given propeller and operating conditions. While this methodology is developed, a greater emphasis will be possible on specific effects of the different fin parameters like placement angle, cross sectional shape, height etc. on the effectiveness of fin which will further help in developing optimisation models for the fin development and design as the requirement of highly efficient fins goes up and the gap between the optimum and the most efficient design has to be bridged. The future scope of the work also includes the more comprehensive analysis of the already developed fins pertaining to factors like cavitation, hull resistance and the case of disturbed inlet flow instead of the uniform inlet flow as considered in this study. The study definitely shows that PBCF are effective in being developed as Energy Saving Devices (ESDs), the effectiveness of which depends slightly over the operating ranges of a particular propulsion system.

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