CFD Analysis on Propeller Performance with Propeller Boss Cap Fin

Swapnil D. Sankpal, B.M. Shameem

Abstract: ***The global price of oil, which is both finite and limited in quantity, has been rising steadily because of the increasing requirements for energy in both developing and developed countries. Furthermore, regulations have been strengthened across all industries to address global warming. Many studies of hull resistance, propulsion and operation of ships have been performed to reduce fuel consumption and emissions. The present study examined the design parameters of the propeller boss cap fin (PBCF) and hub cap in improving the propeller efficiency. PBCF is the kind of hydrodynamic energy saving device which aims to reduce energy losses associated with propeller hub vortex by fitting fins to the cap of a propeller. The main principles of PBCF is breaking up hub vortex to straighten propeller wake, thus recovering the negative pressure on the cap. This reduces propeller's rotational losses and produces negative torque to reduce propeller shaft torque and generating thrust. The study focuses on the size of the blades on boss cap and optimizing its geometry using CFD technique. Open Water Test has been modelled using dynamic meshing technology known as overset meshing. Seven variations of PBCF are modelled and tested to estimate the efficiency of the propeller. The obtained results are then compared with the simulation result with the propeller without PBCF arrangements. The propeller characteristics (without PBCF) has been initially validated using overset meshing strategy with the available experimental results. Overset mesh has been used to perform this analysis to give better control over the fluid flow. It has been observed that, the propeller with PBCF, one among seven variations is giving nearly 2.0% more efficient than the propeller without PBCF.***

Keywords* : *Propeller Boss Caps Fins, CFD, Hub Geometry, Energy Saving Device

I. INTRODUCTION

Waste of fuel and exhaust pollution is now one of the problems in the field of shipping. As an effort to retrenchment fuel and reduce air pollution due to flue gas, the shipping worlds have begun to develop various Energy Saving Devices (ESDs). The International Maritime Organization (IMO) enacts an Energy Efficiency Design Index (EEDI) which is scheduled in January 2014 to reduce carbon-dioxide on shipping operation and building. The development of ESDs is an effort to improve the ship performance and its operations with lesser emission of CO_2 [6].

The engine performance is mainly affected by the efficiency of the propeller. The energy saving devices attached to the propeller or region of flow is aimed to increase the propeller efficiency by reducing the lost flow. The loss of flow around propeller is caused by the slip on the blades, the wake flow inequality leading to rotation of the blades, hub or tip vortex. The generation of hub vortex is one of the problems affects the propeller performance [7]. With the emerging vortex on the propeller hub, it will reduce the speed and decrease the efficiency of the blades. Not only reduces the performance of the blades, but also erodes the rudder. The interaction between rudder and propeller creates several problems such as cavitation caused by low velocity of the vessel, periodic impact due to rotation of the blades to ship structure or rudder, undefined natural side force due to hydrodynamic loads.

Many ESDs are often applied on ship propulsion and still under development such as Pre-swirl, Duct, and Propeller Boss Cap Fins. Pre-swirl is placed on the propeller flow region and is designed to apply the propeller flow efficiency, See Fig.1. The pre-swirl placement is between stern and propeller. From the placement of the Pre-swirl flow can lead well towards the propeller. Pre-swirl focuses wake flow which has an opposite rotating stream with propeller. Pre Swirl can regenerate the drag from the hull of the vessel to positive thrust and improve the efficiency [3].

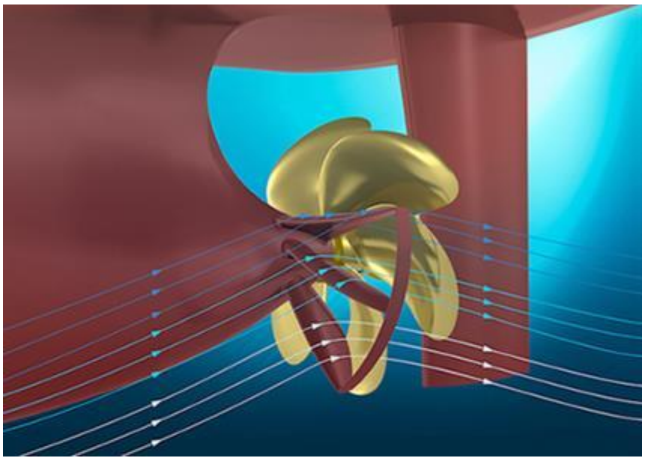

Fig. 1. Typical arrangement of Pre-Swirl

The duct can also be called a nozzle mounted around the propeller and its function focuses the flow from hull to propeller shown in Fig. 2. The duct can reduce the wasted axial flow of the propeller, reduce thrust deduction, and increase uniform flow. The duct can increase thrust propeller by supporting stator to regenerate thrust to positive and increase the efficiency [4].

Manuscript published on November 30, 2019.
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Fig. 2. Ship with ducted propeller [5]

The improvement of the propeller performance may possibly with the idea of developing Propeller Boss Cap Fins (PBCF) with additional fins on the boss cap propeller. The additional fins reduces the hub vortex and thus improving the propeller efficiency. PBCF can increase thrust and decrease propeller torque by removing hub vortex due to rotation generated by the fins. A typical arrangement of PBCF is shown in Fig 3.

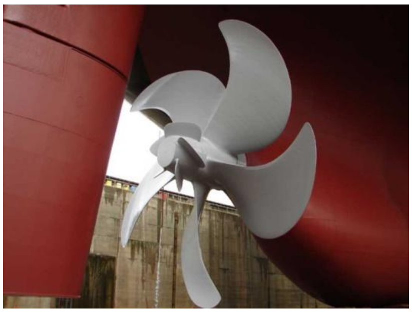

Fig. 3. Propeller Boss Caps Fins (PBCF) [3]

Studies have been carrying out to improve the PBCF performance. The main parameter affects the PBCF performance is its shape and the slope angle of the fins. Further studies are needed to focus on the slope angle of the PBCF to obtain the optimum PBCF design. The objective of the present study is to numerically analyse the performance of the propeller using different variations of PBCF, to propose the PBCF type that can provide better efficiency. The study has been carried out in two different phases, initially validating the open water tests with the available experimental results to validate the computational setup generated in CFD. The validated setup is then used for carrying out different simulation conditions with PBCF arrangements to obtain the optimum efficient combination of the propeller and the PBCF.

II. MODELLING OF PBCF

For the present study, seven types of PBCFs are selected and modelled along with the propeller. The selection of PBCF is carried out with respect to the nature of blade, diameter and area of the blades. The following points are considered for the selection of PBCF.

- The number of fins should be equal to the number of blades of the propeller, this is considered for reducing the wake.
- The phase difference between the cross-section of the blade root and the fins varies from 20 to 30 degrees. This represents the inflow velocity, angle of attack and rotational speed of the propeller.
- The diameter of the fins should not exceed 33% of the propeller's diameter [2]. If the surface area increases above this limit, the fins starts producing torque and hence reduces the overall efficiency of the propeller.
- The leading edge of the fins is located between the roots of two adjacent blades and hence the total impact of the wake is considered.

Table 1 and 2 shows the particulars of the propeller and PBCF and Table 3 gives the variations considered for the selection and modelling of PBCF.

Table - I: Particulars of Propeller

Parameters	Value
Diameter of ship propeller (m)	6.600
Expanded blade area ratio	0.4377
Propeller pitch ratio, mean	0.8250
Chord length-diameter ratio (0.7R)	0.2447
Max. blade thickn. -dia. ratio (0.7R)	0.0167
Hub-diameter ratio	0.1600
Rake angle (deg)	0
Skew angle (deg)	22. 34
Number of blades	4
Turning direction	R.H.
Propeller section type	NACA66
Scale factor	26.4

Table - II: Particulars of Propeller Boss Cap Fin (PBCF)

Parameters	Value
Number of blades	4
Turning direction	R.H.
Diameter	Variable
Angle of installation	Variable
Chord of fin	Variable

Table - III: Variation in Cap Fin of PBCF

Cases	Nature of blade	d/D	a/A
Case 1	More square shaped at edge	0.30	0.39
Case 2	No Camber with square edge	0.41	0.38
Case 3	Slid Camber with rounded edge	0.17	0.25
Case 4	Slid Camber with square edge	0.25	0.26
Case 5	High Camber with square edge	0.25	0.27
Case 6	Moderate Camber with rounded edge	0.30	0.37
Case 7	Same as propeller blade	0.65	0.62

where, d- diameter of PBCF, D- diameter of propeller, a - blade area of PBCF and A-Blade area of propeller.

A scale factor of 1:26.4 is used for modelling the propeller, for validating the available experimental results. The propeller with PBCF is modelled along with seven variations. Propeller and PBCF contain sharp edges and it is very important to model the blades precisely to generate proper meshing on its surfaces. The 3D modelling of the propeller and PBCF is carried out in PropCad software, See Fig 4.

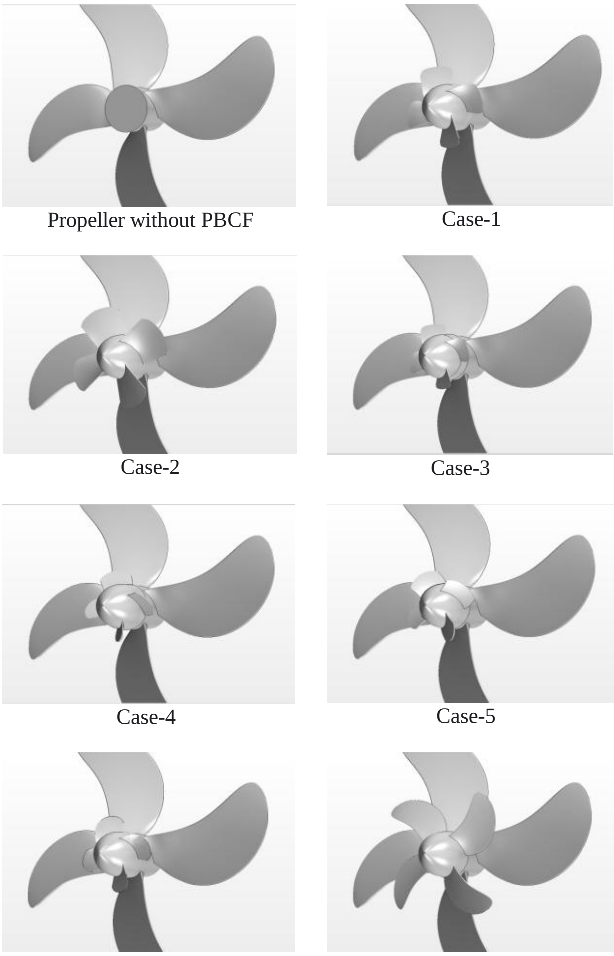

Fig. 4. Modelling of different PBCF with Propeller

III. NUMERICAL SETUP AND ANALYSIS

The problems related to ship hydrodynamics is sometimes difficult to predict using captive or free running tests, due to the requirement of sophisticated measurement tools for instantaneous estimation and visualization. The usage of CFD solver for ship hydrodynamics includes many applications. The important division in a CFD solution process is to accomplish an appropriate domain and meshing strategy to obtain a converged solution. To minimize the wall effect, the domain has to be fixed far from the object. The setting of the domain size usually carried out after analysing through domain study to reach an appropriate dimension and hence the effects are minimum or negligible. For open water tests, generally in the literature a cylindrical domain is used. The domain size for the open water tests used for the present study is as per ITTC recommendations [2].

To generate the simulation of rotating propeller it is more feasible to use the dynamic meshing strategies such as sliding or overset grid methods [1]. Here the overset meshing strategy is used for computation. The domain is spilt into two components, a background and an overset region. Overset region consist of the propeller or propeller with PBCF and in the background, numerical tank is considered for the fluid flow. An additional refinement region around the propeller is created for refining the mesh around the propeller. To execute the overset meshing, there should be an overlap region which contains the overset and the background region. This overlap is for transferring the simulation data. The domain setup for dynamic meshing that is generated for the propeller open water simulations with and without PBCF is shown in Fig 5.

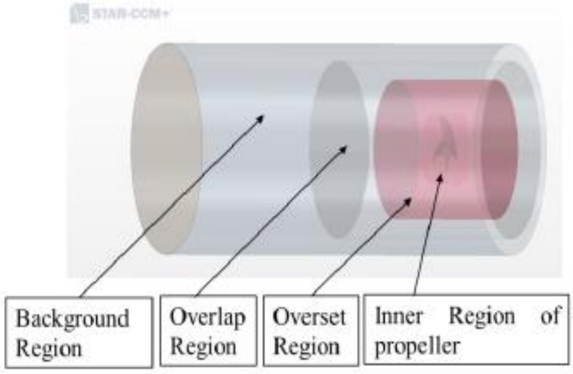

Fig. 5. Domain Setup - Open Water Test

The mesh generation is carried out using the automatic mesh generator in STARCCM+ with trimmed hexahedral cells. An additional near wall prism layers are imposed around the propeller to capture the boundary layer effects. The k-epsilon turbulence model is used to simulate the turbulence characteristics. Fig 6 and 7 shows the mesh generation around the propeller and the distribution of mesh in the x-z plane. The view of overall mesh in the computational domain is shown in Fig 8.

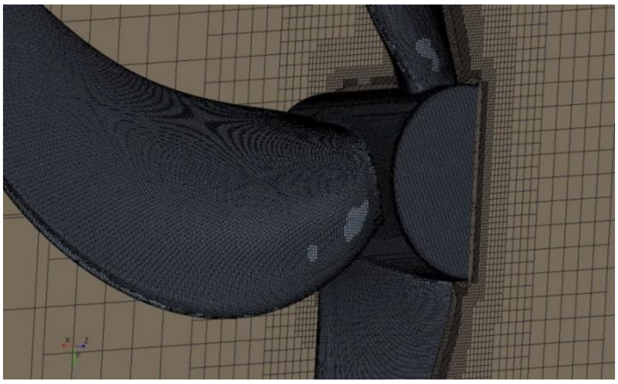

Fig. 6. Mesh around the Propeller

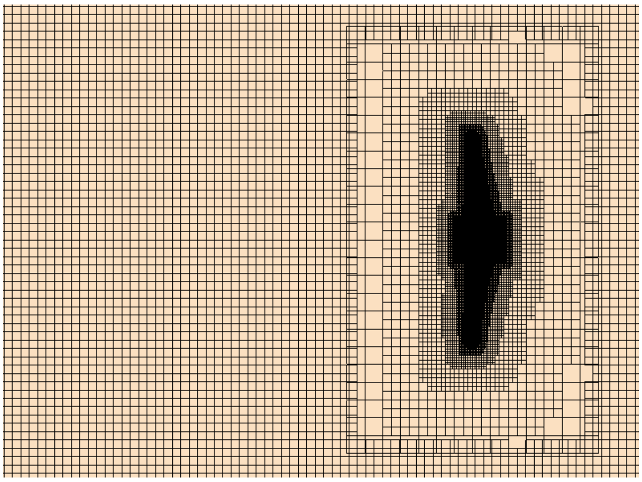

Fig. 7.View of mesh distribution in x-z plane

Retrieval Number: D9795118419/2019©BEIESP
DOI:10.35940/ijrte.D9795.118419
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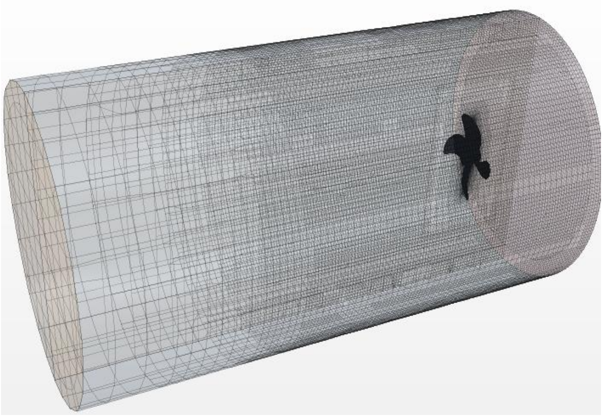
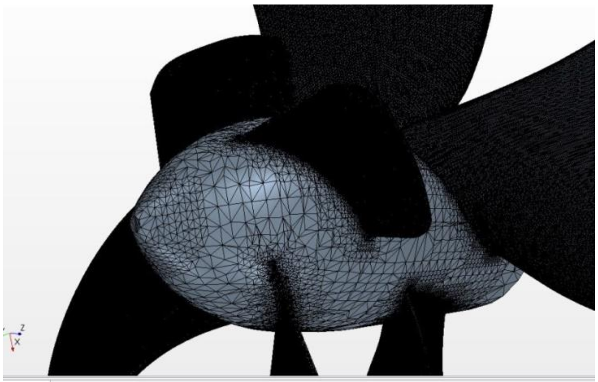
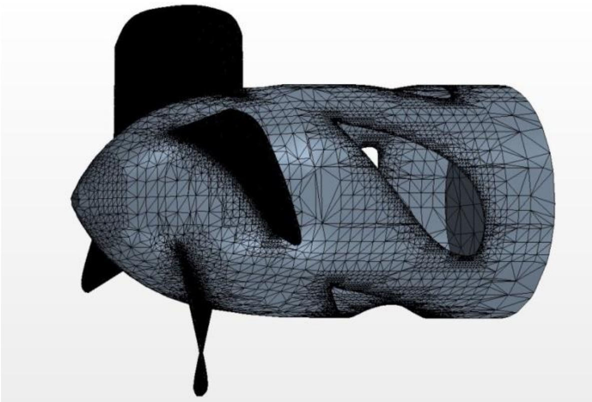


Fig. 8.Mesh on the computational domain

The same setup is used for the computations using the propeller with PBCF. The view of surface mesh generated on the propeller with PBCF is shown in Fig 9.



(a) View of surface mesh on PBCF



(b) View of surface mesh on propeller and PBCF

Fig. 9. Mesh around the propeller with PBCF

IV. RESULTS AND DISCUSSION

In the first phase of the study, the open water simulation results are validated with the available experimental results to check the reliability of computational setup and the meshing strategy. All simulations are carried out using advanced computational software, Siemens STARCCM+ in Intel i7 – 4.2 GHz processor. To complete one simulation, it took 48 hours' time with this processor. The results obtained for thrust coefficient (Kt), torque coefficient (Kq) and propeller efficiency through the open water CFD simulations and the comparison with the experiments is shown in Fig 10. The results tabulated for the propeller efficiency is given in Table 4. It has been observed from the simulations that the error percentage is slightly increasing for higher advance coefficient, J. The whole simulations are carried out with same mesh configuration. This error may be reduced by using a different mesh configuration at higher advance coefficients with the overset meshing technology. The same trend is visible in the case of propeller simulations with PBCFs.

Table – IV: CFD validation for efficiency without PBCF

J	ETA (CFD)	ETA (EFD)	Error %
0.1	0.12841	0.134	4.35
0.2	0.2517	0.262	4.09
0.3	0.3665	0.382	4.22
0.4	0.468	0.493	5.34
0.5	0.55006	0.59	7.26
0.6	0.60508	0.669	10.56
0.7	0.6034	0.72	19.32

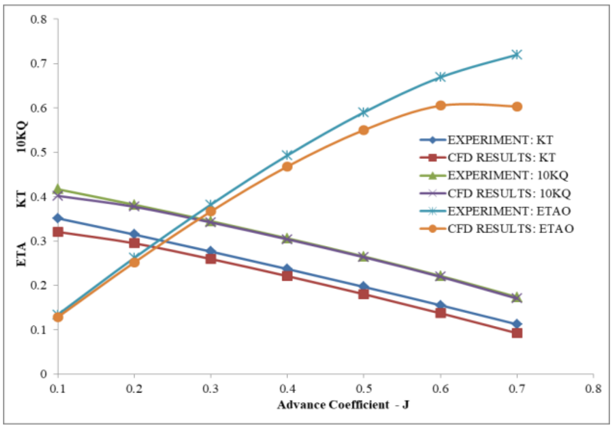


Fig. 10. Comparison of Kt, Kq and propeller efficiency

In the second phase of the simulation, with the same computational setup, the propeller geometry is replaced with propeller with PBCFs for seven different variations. The thrust, torque and the efficiency of propeller with the PBCF arrangements are computed. The propeller with PBCF, case 6, has shown better performance with an increase in efficiency of nearly 2% at low advanced coefficients. The percentage increase in the propeller efficiency is tabulated for each cases and presented in Table 5 to 10. The comparison in of PBCF variations are plotted and shown in Fig 11.

Table – V: Comparison of propeller efficiency (Case 1)

J	ETA-- Without PBCF	ETA -- With PBCF (Case 1)	Increase in efficiency (%)
0.1	0.1284	0.1307	1.7295
0.2	0.2517	0.2559	1.6413
0.3	0.3665	0.3713	1.2928
0.4	0.4680	0.4725	0.9524
0.5	0.5501	0.5534	0.6035
0.6	0.6051	0.6037	-0.2286
0.7	0.6034	0.5983	-0.8524

Table – VI: Comparison of propeller efficiency (Case 2)

J	ETA-- Without PBCF	ETA -- With PBCF (Case 2)	Increase in efficiency (%)
0.1	0.1284	0.1303	1.4505
0.2	0.2517	0.2552	1.3715
0.3	0.3665	0.3699	0.9192
0.4	0.4680	0.4697	0.3619
0.5	0.5501	0.5473	-0.5043
0.6	0.6051	0.591	-2.3824
0.7	0.6034	0.5716	-5.5633

Table – VII: Comparison of propeller efficiency (Case 3)

J	ETA-- Without PBCF	ETA -- With PBCF (Case 3)	Increase in efficiency (%)
0.1	0.1284	0.1307	1.7446
0.2	0.2517	0.2559	1.6413
0.3	0.3665	0.3713	1.2928
0.4	0.4680	0.4725	0.9524
0.5	0.5501	0.5535	0.6215
0.6	0.6051	0.6037	-0.2286
0.7	0.6034	0.5984	-0.8356

Table – VIII: Comparison of propeller efficiency (Case 4)

J	ETA-- Without PBCF	ETA -- With PBCF (Case 4)	Increase in efficiency (%)
0.1	0.1284	0.1287	0.2253
0.2	0.2517	0.2526	0.3563
0.3	0.3665	0.3677	0.3264
0.4	0.4680	0.4696	0.3407
0.5	0.5501	0.5523	0.4056
0.6	0.6051	0.6069	0.2999
0.7	0.6034	0.6105	1.1630

Table – IX: Comparison of propeller efficiency (Case 5)

J	ETA-- Without PBCF	ETA -- With PBCF (Case 5)	Increase in efficiency (%)
0.1	0.1284	0.1292	0.6115
0.2	0.2517	0.2535	0.7101
0.3	0.3665	0.367	0.1362
0.4	0.4680	0.4689	0.1919
0.5	0.5501	0.5523	0.4056
0.6	0.6051	0.6061	0.1683
0.7	0.6034	0.6099	1.0657

Table – X: Comparison of propeller efficiency (Case 6)

J	ETA-- Without PBCF	ETA -- With PBCF (Case 6)	Increase in efficiency (%)
0.1	0.1284	0.1310	1.9771
0.2	0.2517	0.2567	1.9478
0.3	0.3665	0.3723	1.5579
0.4	0.4680	0.4736	1.1824
0.5	0.5501	0.5549	0.8722
0.6	0.6051	0.6049	-0.0298
0.7	0.6034	0.5979	-0.9199

Table – XI: Comparison of propeller efficiency (Case 7)

J	ETA-- Without PBCF	ETA -- With PBCF (Case 7)	Increase in efficiency (%)
0.1	0.1284	0.1269	-1.1899
0.2	0.2517	0.2488	-1.1656
0.3	0.3665	0.3605	-1.6644
0.4	0.4680	0.4555	-2.7442
0.5	0.5501	0.5521	0.3695
0.6	0.6051	0.6058	0.1189
0.7	0.6034	0.609	0.9195

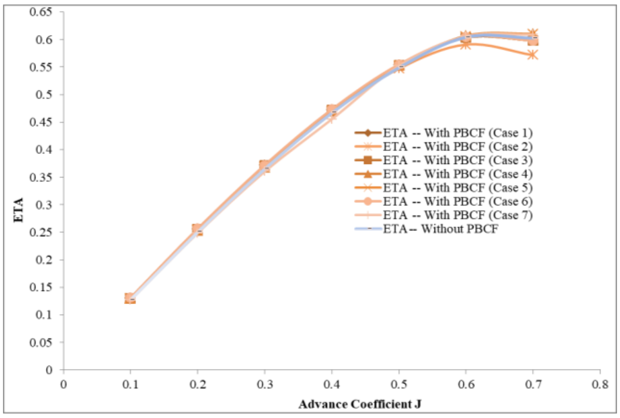
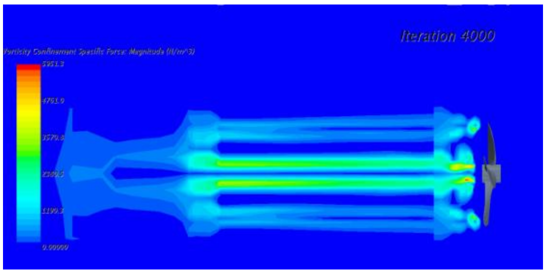
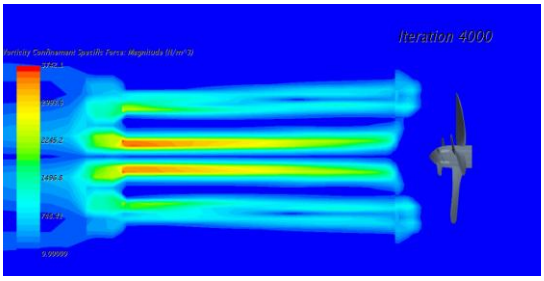


Fig. 11. Comparison of efficiency with different PBCF

The hub vortex generated by the propeller and combination with the PBCF is compared and shown in Fig 12. It has been observed that the incorporation of the PBCF has improved in straightening the propeller wake flow. The images of axial velocity and velocity vector obtained due to the rotation of the propeller with and without PBCF shows that the negative pressure on the cap would be recovered, reducing the propeller's rotational losses and producing negative torque to reduce the shaft torque for generating more thrust, See Fig 13 and 14.

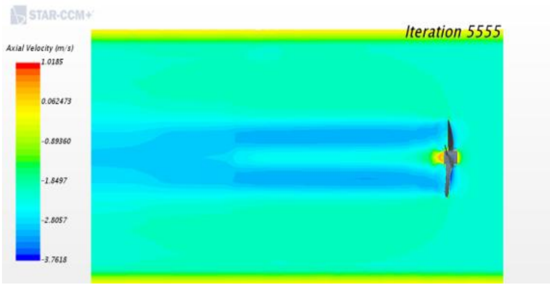


(a) Propeller without PBCF

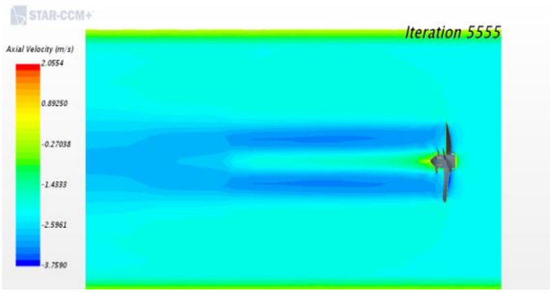


(b) Propeller with PBCF

Fig. 12. Vorticity confinement specific force around the propeller; without and with PBCF (Case 6)

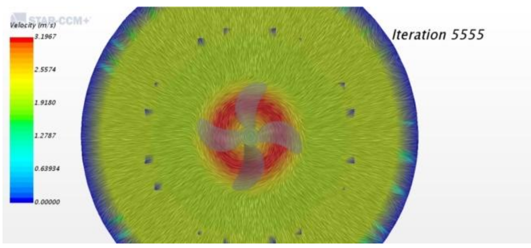


(a) Propeller without PBCF

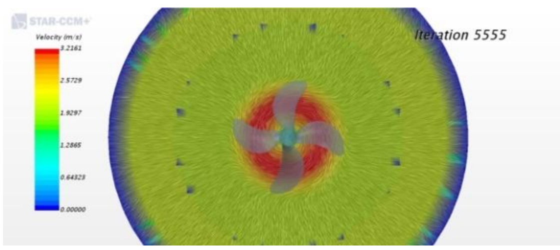


(b) Propeller with PBCF

Fig. 13. Axial Velocity Around the propeller, without and with PBCF (Case 6)



(a) Propeller without PBCF



(b) Propeller with PBCF

Fig. 14.Velocity vector around the propeller, without and with PBCF (Case 6)

V. CONCLUSION

CFD analysis on propeller characteristics with and without PBCF is presented in this paper. To find the most efficient PBCF combination with the propeller, seven different variations of PBCF is modelled with respect to its nature of blades. The angle of installation of the fin and its phase difference against the propeller are two significant parameters should be considered in the design and modelling of the fins. The incorrect consideration may lead to the degradation of the propeller performance. The PBCF with a moderate camber with rounded edge, i.e., Case 6 provides better efficiency than any other combinations. The shape of the PBCF profile satisfies the standard requirements as explained in Section 2. It has been observed that the propeller with PBCF reduces the downstream induced effects of the propeller and makes the downstream flow more uniform, thus improving in the efficiency. Further studies should be carried out to improve the propeller efficiency in behind ship condition by analysing PBCF with Mewis Duct.

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