AN INVESTIGATION ON ITTC 78 SCALING METHOD FOR UNCONVENTIONAL PROPELLERS

Surya Kiran Peravali*[1], Rickard Bensow[1], Walter Gyllenram[2] and Abolfazl Shiri[2]
[1]Department of Shipping and Marine Technology, Chalmers University of Technology
Campus Lindholmen, SE-41296, Gothenburg, Sweden
*peravali.suryakiran@gmail.com, rickard.bensow@chalmers.se
[2]SSPA Sweden AB, Chalmers Tvärgata 10, P O Box 24001, SE-40022, Gothenburg, Sweden
walter.gyllenram@smhi.se, abolfazl.shiri@sspa.se

ABSTRACT: The effort to find solutions to the environmental and energy saving problems regarding the operation of ships is always a matter of concern. Several new unconventional propeller designs have been introduced in recent years. These unconventional propellers are designed with non-planar lifting surfaces and a design approach to improve the energy efficiency by reducing the tip vortex loss and having a better lift/drag ratio. Suspicions have been raised that the standard methods for evaluation of model tests such as the ITTC 78 method does not take the full effect of unconventional propellers in to account [1]. In the present investigation, the performance of two propellers (one conventional and one unconventional) are analyzed using CFD (RANS) in model and full scale in different operating conditions (open-water and behind a hull). The validation studies are performed in model scale and compared with the experimental data. Further the computations are extended to full scale to study the scaling effects on the propulsive efficiency and different propulsive coefficients. The outcome is compared with the predictions from ITTC 78 method applied on different geometries and conditions.

Key Words: unconventional propeller, RANS, scale effect, ITTC 78 method, wake fraction.

1. INTRODUCTION

The ITTC 78 method has been a universal tool for assessing the performance of full scale vessels. The ITTC 78 method has been validated against sea trails over more than 35 years and is very adapted to the conventional propeller designs. For the full scale performance evaluation for the unconventional propeller designs like the Kappel propeller on the basis of model tests, the ITTC 78 method has been normally used. The predicted hull efficiency in full scale is claimed to be lower than in model scale due to the reduction in frictional wake. This discrepancy may be due the methods applied for scaling the wake and open water tests. Hence, the introduction of unconventional propeller designs like the Kappel propeller seem to challenge the traditional ITTC 78 method.

This paper presents a comparative study in various aspects of the performance of a conventional propeller with an unconventional propeller (Kappel propeller). The study is carried out using open source simulation tools (OpenFOAM) for computing viscous flow around a ship hull, propellers in open-water and behind the hull. The numerical results are validated by comparing with the model scale experiments performed at SSPA. Further the computations are extended to full scale in order to study the scaling effects on the propulsive efficiency and different propulsive coefficients. The differences in scaling between the conventional and unconventional propellers are examined and further this relative differences are compared with that of ITTC 78 scaling method.

2. APPROACH

The conventional propeller and a Kappel propeller have been tested at SSPA at 1/37 scale. Both propellers are analysed at model and full scale Reynolds numbers using OpenFOAM RANS viscous flow solver. The computational domain was dicretized using the built in open-source meshing tools in the OpenFOAM environment. Calculations were made using the $k-\omega$ SST turbulence model. In some test cases, wall functions are used to simulate the boundary layer. The following test cases are analysed for the study:

- Bare hull in model and full scale.
- Both propellers in open-water condition in model and full scales.
- Both propellers behind the same hull in self propulsion conditions in model and full scales.

The open-water simulations are carried out using a single-phase RANS solver (`simpleFoam`) in rotating reference frame. The open-water thrust, torque and efficiency are estimated for different advance ratios. For the self-propulsion cases the flow is simulated using the transient RANS solver (`pimpleDyMFoam`) with dynamic/moving mesh capabilities (AMI). The effect of free surface and trim is not considered for the bare hull and self propulsion test cases. Since, a comparative study is performed between the two propellers, the effects of the trim and free surface should be reduced. The computations are carried out for the same ship speed and propeller revolution rate as model tests. For full scale the computations are carried out at same ship speed and propeller revolution rate predicted by the ITTC 78 method. For self-propulsion cases, the performance ranking between the two propellers is compared with the experimental tank test results and the ITTC 78 predictions.

3. VISCOUS FLOW COMPUTATION

For this study, the simulations were performed using OpenFOAM 2.4.x version. OpenFOAM has a collection of libraries dedicated for the solution of partial differential equations (Navier-Stokes). In OpenFOAM solvers, the continuity, momentum and the turbulence equations are solved separately and the pressure-velocity coupling is done using SIMPLE and PIMPLE algorithms. OpenFOAM uses a collocated grid approach and the Rhie-Chow interpolation is used for the pressure velocity coupling. Arbitrary Mesh Interface (AMI) technique is used for the simulation across disconnected, adjacent mesh domains. The domains can be stationary or move relative to one another. This enables to set up a transient simulation with dynamic mesh motion such that the propeller movement is realized by the moving part of the mesh around the propeller geometry.

The first/second order schemes were used for the discretization of governing equations. For gradient terms, second order Gauss linear scheme is used and for the momentum divergence term $(\nabla \cdot (\rho UU))$, the second order scheme Gauss linear upwind is used for the steady state cases and Gamma V scheme is used for the transient cases. The turbulent terms are discretised using bounded Gauss upwind scheme. The second order or conservative Gauss linear corrected scheme is used for the laplacian term $(\nabla \cdot (\nu \nabla U))$. For the transient cases, the time derivative terms $\left(\frac{\partial}{\partial t}\right)$ are discretised using either the first order bounded implicit Euler scheme or the backward scheme.

3.1 Mesh Generation

The meshing for the test cases is performed using the inbuilt `snappyHexMesh` tool in OpenFOAM. The `snappyHexMesh` is an automatic, parallel, octree-refinement based mesh generation utility in OpenFOAM which can create cartesian hexa-dominant meshes and can adequetely handle complex geometries. The test case domains are meshed ranging from 2 million cells to 18 million cells for model scale cases and 10 million to 70 million for the full scale cases. It has been quite expensive to resolve the viscous sublayer $(y+)$ close to the walls for few regions/cases of the geometry. For such regions (log-law region), the wall functions are implemented for the simulation.

3.2 Boundary conditions

In OpenFOAM the case is generally broken into set of patches and the boundary conditions are then assigned as attributes to the patches and to the field variables on a patch. There are various kinds of boundary conditions in OpenFOAM library which are assigned based on the boundary treatment. For the test cases, the boundary conditions are assigned to the flow domain in such a way that the Inlet and Outlet have `inletOutlet` and `outletInlet` boundary conditions respectively. The other bounding faces of the domain are assigned with `slip/symmetry` boundary condition. For the bare hull `noSlip` boundary condition is used. The propeller geometry has a wall type patch attribute with `movingWallVelocity` as velocity boundary condition and `zeroGradient` for pressure boundary conditions. The turbulent variables (k, ω and ν_t) for the wall has a fixes assigned values.

4. RESULTS

4.1 Bare Hull case

The vessel used in this study is a large tanker for which the two propellers (conventional and Kappel) are tested. The flow is simulated using the steady state solver (`simpleFoam`) without a free surface at the design Froude number (0.15). The effect of free surface is neglected as the vessel is steaming with lower Froude number and in order to reduce the complexities in meshing, solution process and convergence. The hull resistance and the nominal wake at the propeller disk are compared with the towing tank tests at SSPA. The resistance predicted by OpenFOAM showed a 5% difference with the experimental result. This difference could be partially due to the effect of free surface. Figure 1 shows the comparison of the nominal wake field at propeller disk between experimental tests and the simulations.The results show a similar trend in the wake with some differences which could be due to various effects like trim, free surface and other interferences in the experimental setup. However, the simulated wake is considered for the study of the scaling effect. Further this bare hull test case is simulated using the commercial CFD tool (Fluent) and compared with the results for OpenFOAM. This is done in order to ensure the accuracy of the open-source tools. The results from OpenFOAM are quite consistant with the results of Fluent. Table 1 show the comparison of resistance between OpenFOAM, Fluent and experimental tests.

Table 1 - Comparison of resistance coefficients using different methods

*	OpenFOAM (snappy)	Fluent (ICEM)	Experiment
Resistance coeff.	0.003768	0.003775	0.003973

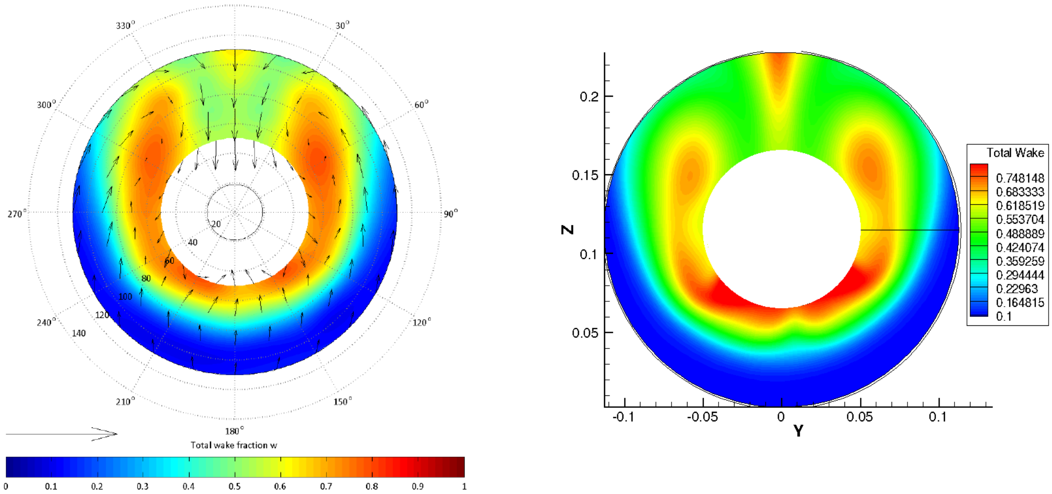

Figure 1 - Wake at the propeller disk from towing tank tests (Left) and through simulation (Right)

4.2 Open-water predictions (Model scale)

The simulations were performed for a conventional and a Kappel propeller which are designed for the same operating conditions. Both the propellers are four bladed and have a shaft length of 1.5 times the diameter of the propeller. The flow is computed for different advance ratios (J) in order to compare the coefficients of thrust (K_T), torque (K_Q) and efficiency (ETA_0) curves for both propellers. Figure 2 shows the model scale open-water predictions of both conventional and Kappel propellers. The solid lines and dashes lines represent the model scale RANS computations of conventional and Kappel propeller respectively. The solid and hollow symbols represent the experimental data. The RANS computations showed good correlation with the experimental data (difference $< 2\%$)) for both the propellers. At higher advance ratios (J>1) the RANS simulations showed a small separated leading edge vortex apart from the usual tip vortex. Currently this phenomenon is not studied as J > 0.6 doesn't fall under design conditions.

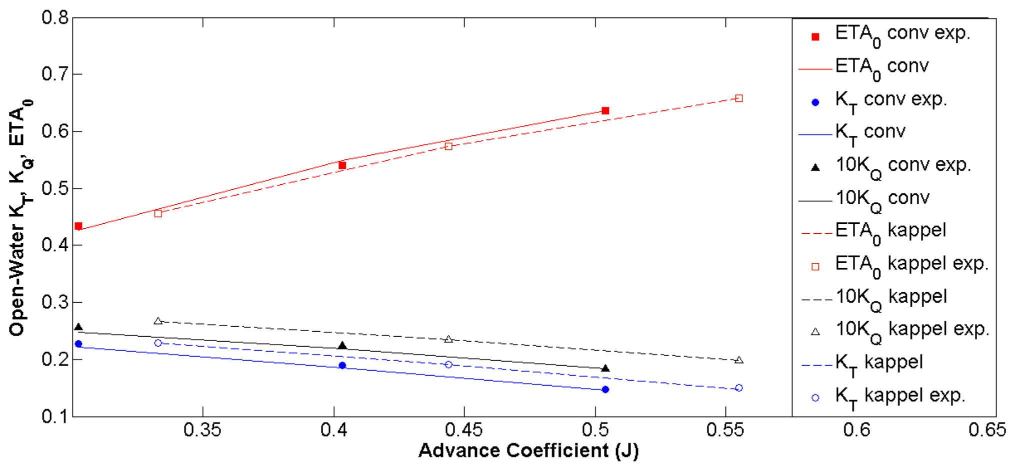

Figure 2 - Open-water non dimesional thrust (K_T), torque (K_Q) and efficency (ETA_0) for conventional and Kappel propeller at model scale

4.3 Self propulsion predictions (Model scale)

For the self propulsion cases, the flow is simulated at the same ship speed (V) and propeller revolution rate as the model tests. The performance is ranked between the two propellers both by CFD and experimentation. Figure 3 (a) shows the difference in propulsive coefficients of Kappel propeller with the conventional propeller at the model test condition. The ranking showed a similar trend in comparison with the experimental performance ranking. Figure 3 (b) compares the effective wake, thrust deduction, hull efficiency and propeller efficiency estimated using CFD between Kappel propeller with conventional propeller. In model scale the Kappel propeller obtains a higher effective wake compared with the conventional propeller. The propeller efficiency is lower for the Kappel propeller and the hull efficiency is higher for Kappel propeller compared with conventional propeller. It is also observed that the conventional propeller has more suction than the Kappel propeller in model scale.

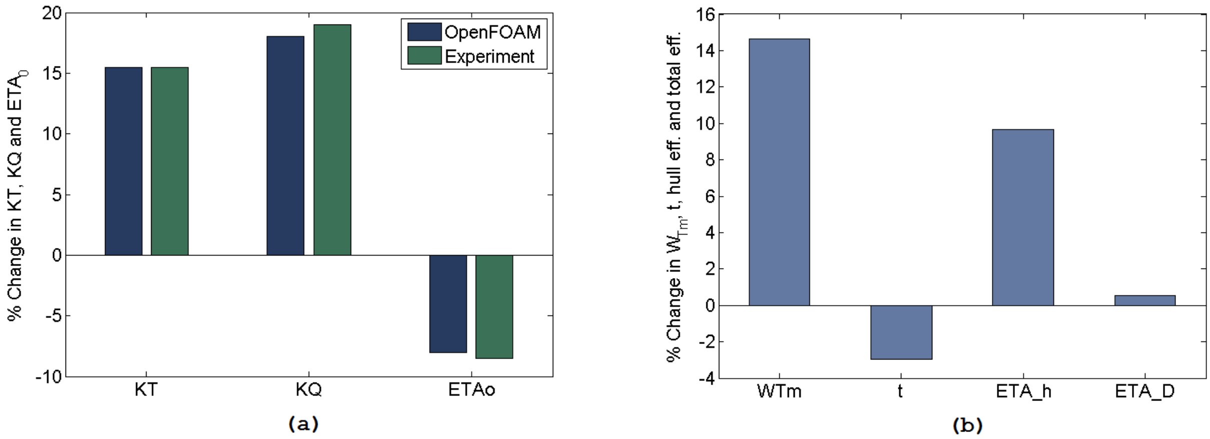

Figure 3 - Difference in propulsive coefficients of Kappel propeller relative to conventional propeller at test condition.

4.4 Open-water predictions (Full scale)

In the 1978 ITTC Performance Prediction Method, the rate of revolutions (n_s) and the design advance coefficient (J_{TS}) are obtained from the full scale open water characteristics. Therefore it is necessary to study the Reynolds scaling effects for a full scale propeller operating in open water condition. The full scale effective wake (W_{TS}) is calculated using formula

$$W_{Ts} = (t+0.04) + (W_{Tm} - t - 0.04)\frac{(1+k)C_{Fs} + \Delta C_F}{(1+k)C_{Fm}}, \quad (1)$$

and then the load of the full scale propeller is obtained by estimating the $\frac{K_T}{J^2}$ ratio which is given by:

$$\frac{K_T}{J^2} = \frac{S_s}{2D^2}\frac{C_{Ts}}{(1-t)(1-W_{Ts})^2 n_p}, \quad (2)$$

where S_s is the wetted surface the hull, D is the propeller diameter, n_p is the propeller revolution rate in model scale and C_{Ts} is the total resistance coefficient. With $\frac{K_T}{J^2}$ as input value, the full scale advance ratio (J_{Ts}) and the torque coefficient (K_Q) are determined from the full scale propeller open water characteristics. The full scale open water characteristics are determined using the ITTC 78 open water scaling method. The rate of revolutions for the full scale propeller is obtained by

$$n_s = \frac{(1 - W_{Ts})V_s}{J_{Ts}D}. \tag{3}$$

The ITTC 78 method is applied to predict the full scale performance through model scale simulations and experiments. The design advance coefficient (J_{Ts}) and propeller revolution rate (n_s) are estimated for both conventional and unconventional propellers.

To study the Reynolds scaling effects at the ITTC predicted J_{Ts}, the propeller test cases for full scale are set up. The simulations are carried out with a design advance coefficient J_{Ts} and propeller revolution rate (n_s), estimated by ITTC 78 method for both propellers. The open water thrust, torque and efficiencies are calculated as in model scale simulations. The percentage change in the scaling corrections of K_T, K_Q and ETA_0 is estimated using both ITTC 78 method and using OpenFOAM RANS simulations.

For both the propellers the ITTC scaled propulsive coefficients didn't show good correlation with the RANS results. The OpenFOAM calculated K_T, K_Q and ETA_0 values are approximately 5-12% higher than the ITTC 78 scaled values. Figure 4 (a) and (b) show the scaling corrections as a percentage change of K_T, K_Q and ETA_0 at a design advance coefficient (J_{Ts}) estimated by the ITTC 78 method (Equation 3). The conventional propeller has a J_{Ts} of 0.486 and Kappel propeller has a J_{Ts} of 0.483. To better understand the differences between model scale and full scale simulations, the integrated pressure and shear stress for thrust and torque are investigated separately. If only viscous shear stresses are considered the model to full scale corrections predicted by RANS simulation reduce greatly (Figure 4 (a) and (b)). This clearly implies that there must be a Reynolds number effect on the blade pressure distributions not captured by the friction coefficient based ITTC 78 method. The viscous-only scaling correction from the RANS simulation is similar to the friction coefficient based ITTC 78 method for both the cases. However, the viscous scaling predicted by RANS is greater than ITTC 78 method. This could be due to the fully turbulent boundary layer assumption in the OpenFOAM simulations.

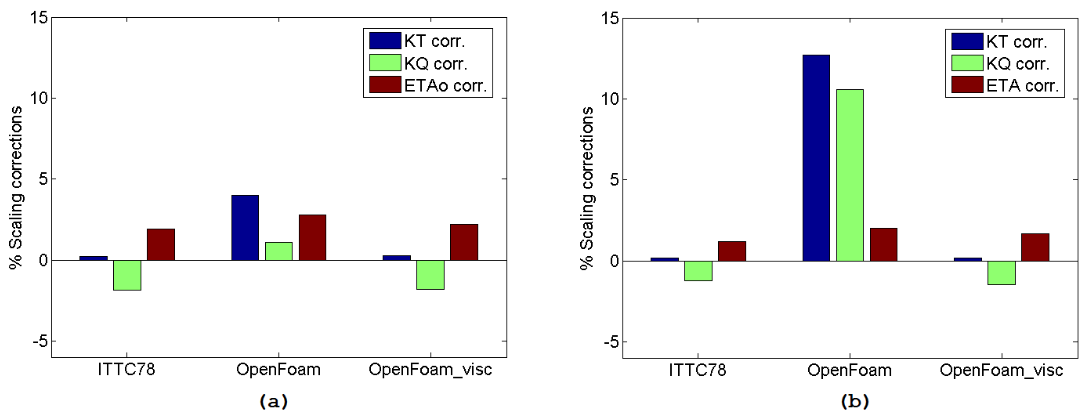

Figure 4 - Reynolds scaling corrections of different methods for conventional propeller (a) and Kappel propeller (b) at ITTC design advance coefficient

Figure 5 (a) show the percentage change of various properties of present Kappel propeller with conventional one at different advance ratios. The full scale simulations of both propellers at the ITTC scaled design advance coefficient (J_{Ts}) show that the Kappel propeller has 2.5% less efficiency than the conventional one. The $\frac{K_T}{J^2}$ value is compared between ITTC 78 method and from the RANS simulation. The $\frac{K_T}{J^2}$ value predicted by RANS is 0.2% under-predicted compared with the ITTC predicted $\frac{K_T}{J^2}$ value for a conventional propeller and 7.3% over-predicted by RANS when compared to the ITTC predicted value for the Kappel propeller. Further the amount of thrust produced by the Kappel propeller is 6.8% higher than the conventional one. This comparison questions the design advance coefficient (J_{Ts}) predicted by ITTC 78 method for the Kappel propeller. Since the $\frac{K_T}{J^2}$ value predicted by ITTC 78 and RANS methods are much coherent, it is deduced that the ITTC 78 method works quite well for the conventional propeller. Therefore, it is assumed that the thrust produced by the conventional propeller is the required thrust (T_{req}) for the operating condition. Now for the Kappel propeller, the advance coefficient is adjusted and flow is simulated till the thrust of the propeller reaches T_{req}. From this simulation, a new design advance coefficient (J_{TsRANS}) is predicted for the Kappel propeller at the operating condition. The RANS predicted design advance coefficient (J_{TsRANS}) has a value of 0.5156 which is 6.6% higher than the design advance coefficient (J_{Ts}) predicted by ITTC 78 method. Figure 5 (b) shows the scaling corrections as a percentage change of K_T, K_Q and ETA_0 at design advance coefficient (J_{TsRANS}). At J_{TsRANS}, the Kappel propeller has 7.2% higher efficiency than the conventional one. The viscous-only scaling corrections show that the Kappel propeller has 3.3% higher efficiency than the conventional propeller. (Note: For conventional propeller $J_{TsRANS} = J_{Ts}$ and for Kappel propeller $J_{Ts} < J_{TsRANS}$.)

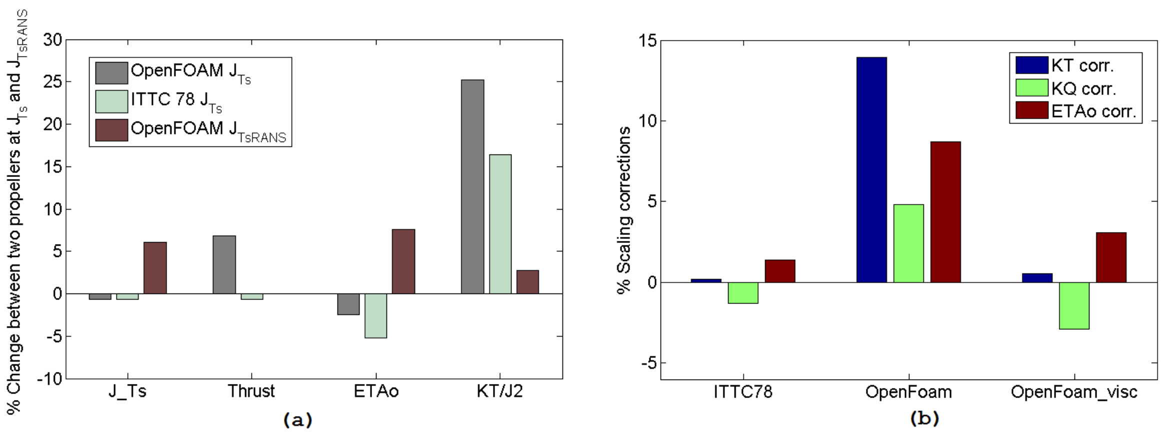

Figure 5 - (a) Difference in properties of the present Kappel propeller with the conventional propeller at J_{Ts} and J_{TsRANS}. (b) Reynolds scaling corrections of different methods for Kappel propeller at design advance coefficient (J_{TsRANS}).

The ITTC 78 procedure arrive at a full scale propeller characteristics by correcting the model test results for model to full scale friction differences at a representative radius r/R =0.75. This assumption has been questioned for the Kappel propeller due to unique tip geometry and load distribution [1]. Comparing Figure 4 (a) and 5 (b), it can be observed that at J_{TsRANS} the OpenFOAM viscous scaling effect on propulsive coefficients for the conventional propeller is less than that of the Kappel propeller. The viscous scaling effect on efficiency is about 2% for conventional propeller and 3.5% for Kappel propeller at J_{TsRANS}, while the ITTC 78 efficiency scaling is less than 2% for both the propellers. This study explains the increase in viscous scaling effects due to the additional surface at the tip of the Kappel propeller. Further the ITTC 78 procedure over-predict the $\frac{K_T}{J^2}$ value which questions the load calculation formula (Equation 2) and the ITTC 78 wake scaling formula (Equation 1). To analyse this discrepancy there is a necessity to compare the self propulsion tests in model and full scale.

4.5 Self propulsion predictions (Full scale)

The performance of the two propellers operating behind a hull is evaluated in full scale. The flow is simulated at the same ship speed (V_S) and propeller revolution rate (n_s) estimated by the ITTC 78 performance prediction method. Again, there is no consideration of free surface in the simulation. The ranking between the two propellers is compared with the predictions of the ITTC 78 method. For estimating the effective power of the hull, the flow is simulated around the bare hull without the propeller.

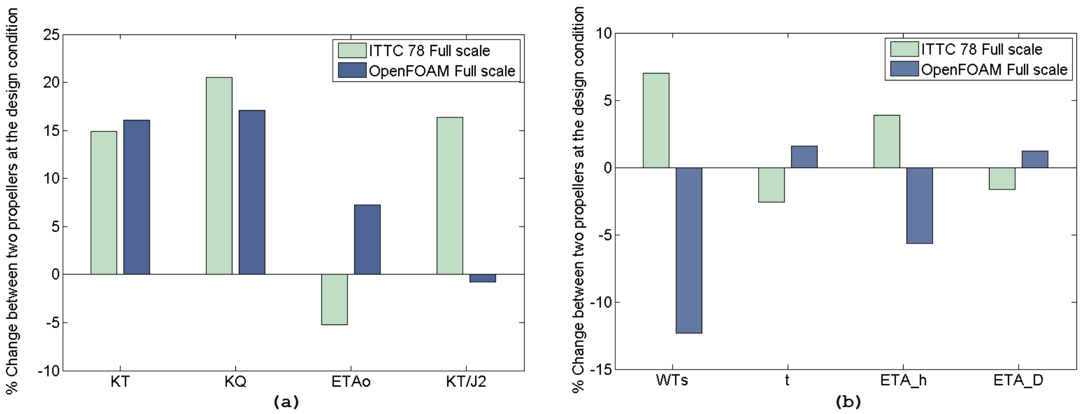

Figure 6 - Difference in propulsive coefficients of Kappel propeller relative to conventional propeller using ITTC 78 and OpenFOAM

In Figure 6 (a) the percentage change of various propulsive factors (K_T, K_Q, ETA_0 and K_T/J^2) between both the propellers is compared with the ITTC 78 full scale design condition (i.e same ship speed and rps of the propeller). Figure 6 (b) shows the difference in the effective wake fraction (W_{Ts}), thrust deduction (t), hull efficiency (ETA_h) and total efficiency (ETA_D) respectively. The prediction of the RANS forecasted the condition of the two test cases to be under propelled. At this under propelled condition the full scale advance ratios (J_{Ts}) of conventional and Kappel propeller are 0.4931 and 0.5335 respectively. However, the ITTC 78 estimates J_{Ts} for conventional propeller to be 0.486 and 0.482 for the present Kappel propeller.

The RANS assessment at the full scale design condition showed that the present Kappel propeller obtains lower effective wake and hull efficiency than the conventional one. It also estimates that the present Kappel propeller has a higher propeller and propulsive efficiency than the conventional propeller. However, the ITTC 78 performance prediction method estimates that the present conventional propeller has a lower effective wake and hull efficiency than the Kappel propeller. It also estimates that the propeller and propulsive efficiencies are higher for the present conventional compared to the Kappel propeller. It is also observed that the Kappel propeller has more suction than conventional one in full scale.

5. CONCLUSION

In this paper, the authors have presented a comparative study of performance between a Kappel propeller and a conventional propeller having the same operating profile. The scale effects have been investigated for propellers using both ITTC 78 method and OpenFOAM RANS. The pressure and viscous effects are studied separately to better understand the scaling effects. If only the changes in viscous stresses are considered the model to full scale corrections correlate well with the ITTC 78 corrections. This justifies the friction coefficient based ITTC 78 method. Further this study show that there is a Reynolds number effect on blade pressure distributions which is not taken into account by the ITTC 78 method.

The ITTC 78 procedure estimates the full scale propeller characteristics by correcting the model test results for model to full scale friction differences at a representative radius r/R =0.75. This assumption has been questioned for the Kappel propeller due to unique tip geometry and load distribution [1]. In support of this, the RANS scaling also showed an addition scaling effect on the Kappel propeller compared with the conventional propeller. The Kappel propeller showed higher propeller efficiency and lower delivered power at RANS predicted design advance coefficient (J_{TsRANS}).

The performance of the present conventional and Kappel propeller behind a hull is evaluated using RANS and the ITTC 78 method at same ship speed (V_s) and propeller revolution rate (n_s). The results from the RANS didn't correlate well with the ITTC 78 method for Kappel propeller. The RANS analysis predict that the present Kappel propeller obtains lower effective wake than the conventional one (about 12%) at this particular design condition in contradiction to the ITTC 78 method. The full scale RANS investigation on various efficiencies of the propeller showed that the present Kappel propeller has higher propeller efficiency (about 7.3%) and total efficiency (about 1.23%) compared to the conventional propeller contradicting the ITTC 78 method. However, the hull efficiency is higher for the present conventional propeller (about 5%).

The Reynolds number effect on blade pressure distributions of Kappel propeller necessitated further investigation on full scale open-water performance. From the RANS assessment of the propellers in open-water and behind the hull conditions showed that the ITTC 78 over predicts the load on the propeller (K_T/J^2) which could be due to the discrepancies in wake scaling. Further it was observed that at the design condition the present Kappel propeller obtains much higher drag (about 14%) compared to conventional propeller in model scale. In full scale, this difference was smaller (about 6%) and this additional drag in model scale could affect the scaling of the propeller operating in a wake field. However, all these constraints needed a further investigation. The influence of free surface is yet an another important factor which affects the effective wake which have not been investigated in the present study.

6. AKNOWLEDGEMENTS

The authors would like to express their appreciation to the SSPA Sweden AB, which was supporting the project. Special thanks are given to the MAN Diesel and Turbo, Denmark for allowing to use their Kappel propeller geometry for investigation.

7. REFERENCES

1. Nielsen, J.R., Kappel, J.J., Bering, R.M. (2014) Scaling of conventional and unconventional propellers. ITTC 2014 conference. Copenhagen.

2. Andersen, P. (1996) A Comparative Study of Conventional and Tip-Fin Propeller performance. 21st Symposium on Naval Hydrodynamics, Trondheim, Norway.

3. Andersen, P., Friesch, J., Kappel, J.J. (2005) Development of a Marine Propeller with Non-planar Lifting Surfaces. Marine Technology 42(3) pp.144-158.

4. Brown, M. , Sanchez-Caja, A., Adalid, JG., Black, S., Perez Sobrino, M., Duerr, P., Schroeder, S., Saisto, S. (2014) Improving Propeller Efficiency Through Tip Loading. 30th Symposium on Naval Hydrodynamics, Hobart, Tasmania, Australia.

5. Sanchez-Caja, A. Sipila, T.P., Pylkkanen, J.V. (2006) Simulation of the Incompressible Viscous Flow around and Endplate Propeller using a RANSE Solver. 26th Symposium on Naval Hydrodynamics, Rome, Italy.

6. Cheng, H., Chien, Y., Hsin, C., Chang, K., Chen, P. (2010) A numerical comparison of end-plate effect propellers and conventional propellers. 9th International Conference on Hydrodynamics, Shanghai, China.

7. Bertetta, D., Brizzolara, S. (2012) EFD and CFD Characterization of a CLT Propeller. International Journal of Rotating Machinery, Volume 2012, Article ID 348939.

8. Gaggero, S. and Brizzolara, S. (2012) Endplate effect propellers: A numerical overview. Sustainable Maritime Transportation and Exploitation of Sea Resources–Rizzuto & Guedes Soares (eds), Taylor & Francis Group, London, ISBN 978-0-415-62081-9.

9. Andersen, P., Kappel, J.J., (2009) Aspects of Propeller Developments for a Submarine. First International Symposium on Marine Propulsors (smp'09), Trondheim, Norway.

10. Peravali, S. (2016) Investigation of Effective Wake Scaling for Unconventional Propellers. "http://studentarbeten.chalmers.se/publication/232455-investigation-of-effective-wake-scaling-for-unconventional-propellers"

11. Gonzalez-Adalid, J., Perez Sobrino, M., et-al (2014) Comparison of different scaling methods for model tests with CLT propellers. 11th International conference on hydrodynamics (ICHD 2014), Singapore.

12. Streckwall, H., Greitch, L., Muller, J., Scharf, M., Bugalski, T. (2013) Development of a strip method proposed to serve as a new standard for propeller performance scaling. Ship Technology Research.

13. Dyne, G., (2005) On the principles of propellers with end-plates. International Journal of Maritime Engineering.

14. Andersen, P., Borrod, AS., Blanchot, H. (2004) Evaluation of the service performance of ships. Marine Technology 42(4) pp.177-183.

15. Lindgren, H., Dyne, G., (1979) Ship performance prediction. International symposium on advances in Marine Technology, Trondheim, Norway.