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Concern of AC of 25th ITTC

"This Procedure describes the best possible methodology based on information currently available. However, users should be aware that a clear scaling procedure has not yet been developed due to the lack of model-scale and full-scale supporting data the public domain. The Procedure may be changed when such data becomes available"

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Procedures for Podded Propulsor Tests and Extrapolation

1. PURPOSE OF PROCEDURES

To describe procedures relating to azimuthing podded propulsors or thrusters, for undertaking the following model tests:

(1) Propeller open water test

(2) Pod unit open water tests

(3) (Self) Propulsion tests,

and for the extrapolation of the results of such model tests to full scale.

All three tests are described here, although some of these tests may be considered as options: not all tests may be required in a particular study of a podded propulsor, or in the extrapolation of model test results, to arrive at a full scale power-speed prediction. It should be noted that in this test and extrapolation procedure, the difference between a mechanical azimuthing thruster unit and an azimuthing podded propulsor is non-existent from a hydro-dynamical point of view and thus both types of propulsors are from here on referred to as "podded propulsors".

The procedure is valid for the two known variants of thrusters/podded propulsors: "pulling" units and "pushing" units. The maximum number of the units taken into account is restricted to 2. The use of nozzles on podded propulsors is in development, although ducted propellers are commonly used on mechanical thrusters. The use of nozzles on electric podded propulsors is now left out of consideration in this procedure and should be treated in future TTC-work. Figure 1 is a simple flowchart showing the sequence and interrelation between the above tests to be able to make power prediction of a pod driven ship in full-scale.

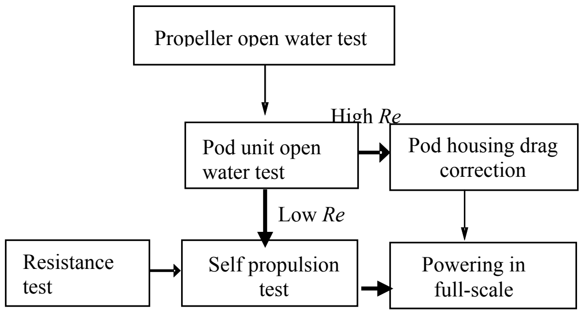


Figure 1 Flow diagram of power prediction of a vessel with podded propulsion

2. DESCRIPTION OF PROCEDURES

2.1 Propeller open water test.

The procedure for open water tests of the propellers for a ship equipped with podded propulsors is basically the same as that of Procedure 7.5-02-03-02.1" Propeller open water tests", (ITTC, 2002b) although some typical aspects for propellers with strongly tapered hubs are not considered and these aspects are given in this section where necessary. The present section emphasizes the special characteristics of propeller open water tests for propellers of podded propulsors. The section is concerned with the tests of a propeller mounted on a drive shaft of an open water test dynamometer without any simulated thruster or pod housing parts.

2.1.1 Test objectives

Propeller open water tests for podded propulsors have mainly three goals:

- Propeller open water characteristics for a design propeller to be used for the prediction of the full scale propeller performance; this aspect being mainly of interest for the propeller designer.
- Propeller open water characteristics to be used for a determination of the propeller-pod housing interaction, by comparing the propeller and podded propulsor open water results.
- Open water characteristics of a stock propeller to be used for determination of data for the propeller design.

2.1.2 Test conditions

Propeller open water tests to be carried out at least for two rates of rotation:

- Close to the rpm of the matching podded propulsor open water test; for an analysis of the propeller-pod housing interaction.
- As high as possible rpm; high enough to minimize Reynolds scale effects (laminar flow effects); this is essential for a prediction of full scale propeller performance for the propeller designer as well as for the speed-power prediction.

2.1.3 Test set-up

Hub and hub cap

For both pulling and pushing units, the propeller model hub should correspond to the realistic propeller hub configuration. For a pushing unit propeller, a stream lined hub cap of sufficient length should be mounted up stream of the propeller hub, its contour should smoothly go from that of the propeller hub to ensure that the flow over the propeller cap smoothly enters the propeller disc without any local flow separation. This is similar to the test set-up for a conventional propeller as described in Procedure 7.5-02-03-02.1, (ITTC, 2002b).In the case of a pulling unit propeller, the propeller hub cap should be an exact geometrical copy of the cap designed for the full scale unit. Generally speaking, small change of the cap geometry has negligible effect on propeller open characteristics. This is similar to the results of propeller open water characteristics of conventional propellers, however, it will be important when the pod operates at a helm angle (in manoeuvring condition).

Aft fairing

The aft fairing for both types of podded propulsor should be made with a slope of not more than 10 degrees between its conical surface and the propeller shaft. An example of aft fairing for a pulling type propeller is shown in Figure 2

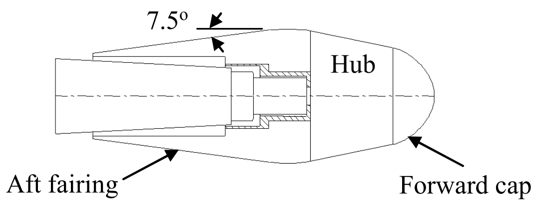


Figure 2 Example of hub geometry for an open water test with a pulling type

For pulling propellers with a big hub cone angle it is acceptable (recommended) to make a more or less cylindrical portion in the aft fairing, to prevent knuckles in the transition from propeller hub to aft fairing. The effect of two aft fairing shapes on the propeller open water characteristics is shown in Figure 3 while some comparative features of these aft fairings are summarized in Table 1 for further information.

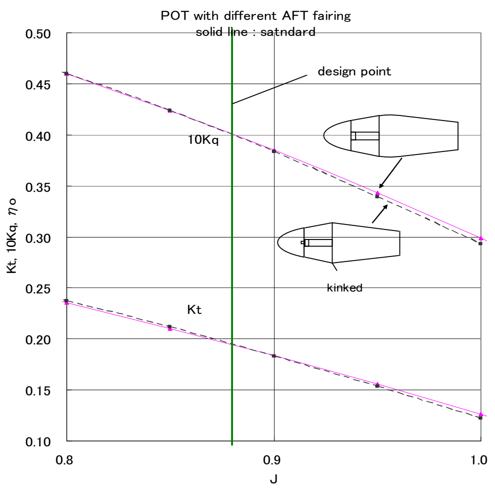


Figure 3 Effect of aft fairing on propeller open water characteristics

The aft fairing can either be fixed to the propeller and thus rotating with the propeller, or be fixed to the test set-up and thus not rotating. In the first case, where the aft fairing rotates with the propeller, a separate pre-test should be done on a similar set-up, but with the propeller replaced by a dummy hub, to be able to correct the propeller open water test results for the effects on thrust and torque of the hub, hub cap and aft fairing piece, thus yielding the open water characteristics of only the propeller blades. (This procedure is similar to the one described in the propeller open water test Procedure 7.5-02-03-02.1, but unfortunately this information is missing there, under the section for a pulling propeller, thus requiring amendment). Using this procedure means that all hub cap, pod housing and propeller gap effects are obtained only in the podded propulsor open water characteristics. This method is preferred for the propeller design since specific characteristics of the propeller hub cone angle and geometry of the hub cap are not in the open water characteristics, but only in the total podded propulsor open water characteristics and are thus assigned to the total podded propulsor performance.

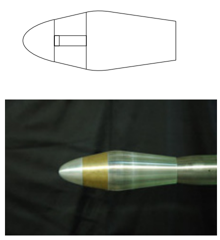
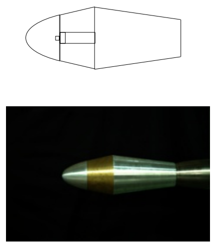
Types	Smooth aft fairing (Recommended)	Knuckled aft fairing
Figures		
Boss resistance	small due to smoothed knuckle	Large due to separation at knuckle
Open water test	flow around hub is similar to that in dummy hub test	flow can be regulated by propeller acceleration
Hub correction	can be applied correctly	can not be applied due to different flow patterns

Table 1 Comparative features of two aft fairing shapes

In the second case, where the aft fairing is not rotating but fixed to the test set-up, the same procedure with pre-runs with a dummy hub have to be done to be able to correct the open water test results to yield only the propeller blade performance. The difference with the first method is that now the difference in gap effect between the pre-test runs and the actual open water test will be contained in the propeller blade open water characteristics. Assuming that the gap effects in open water will be comparable to the effects of the propeller on the pod in the podded propulsor open water test, means that this latter method could be used to distinguish between the separate effects of a typical pulling type propeller and isolated pod housing effects on the pod propeller, in the analysis of a podded propulsor open water test. In general, the first method with the aft fairing connected to and rotating with the propeller is preferred. Table 2 displays some comparative features of the rotating and fixed type aft fairings.

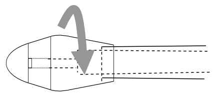
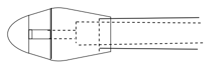
Types	rotating aft fairing	fixed aft fairing
Figures		
Gap effect	no gap effect in both dummy hub test and open water test	two different gap effects with blades and without blades
Advantage	correct blade thrust can be obtained	similar configurations in propeller open water and pod unit open water tests
Disadvantage	gap effect exists only in pod unit open water test	different gap effects propeller open water and unit open water test

Table 2 Some comparative features of rotating aft fairing and fixed aft fairing

Full scale correction

Having conducted the propeller open water tests the full scale correction of propeller K_T and K_Q can be done similar to a procedure used for a conventional propeller alone. One approach is to use the method proposed in the ITTC'78 Extrapolation Procedure as shown below;

The 1978 ITTC Performance Prediction Method gives rate of revolutions and delivered power for the ship (s) obtained from the full scale propulsor open water characteristics. These characteristics are determined by correcting the model ($_{\mathrm{M}}$) values for propeller blade drag scale effects according to the following:

$$K_{T_{\mathrm{S}}} = K_{T_{\mathrm{M}}} + \Delta K_T \qquad K_{Q_{\mathrm{S}}} = K_{Q_{\mathrm{M}}} + \Delta K_Q$$

Where

$$\Delta K_T = \Delta C_D 0.3 \frac{P}{D}\frac{cZ}{D} \qquad \Delta K_Q = -\Delta C_D 0.25 \frac{cZ}{D}$$

The difference in blade drag coefficient is

$$\Delta C_D = C_{D_{\mathrm{M}}} - C_{D_{\mathrm{S}}}$$

where

$$C_{D_{\mathrm{M}}} = 2\left(1 + 2\frac{t}{c}\right)\left[\frac{0.044}{Re_{c_0}^{\ 1/6}} - \frac{5}{Re_{c_0}^{\ 2/3}}\right]$$

and

$$C_{D_{\mathrm{S}}} = 2\left(1 + 2\frac{t}{c}\right)\left[1.89 + 1.62 \log\frac{c}{k_{\mathrm{P}}}\right]$$

In these formulas, c is the chord length of the propeller blades, t is the maximum blade thickness, P/D is the pitch ratio and Re_{c_0} is the local Reynolds number at radius $0.75D/2$

$$Re_{c_0} = \frac{cV}{\nu} \qquad \text{where}$$

$$V = V_{\mathrm{A}}\sqrt{1 + \left(\frac{\pi 0.75}{J}\right)^2} \quad \text{and}$$

ν = kinematic viscosity, in m^2/s (ITTC 1960)

Z = number of propeller blades

k_{P} = full scale blade roughness, which is set to 30 μm

2.2 Pod unit open water test.

2.2.1 Test objectives

Pod unit open water tests have four main goals:-

- To determine the podded propulsor open water performance; either for full scale or for an analysis of podded propulsion tests (to determine the propulsion factors for extrapolation of test results).
- To determine data for the final propeller design (from tests with a stock propeller).
- To optimize the pod units for the pod manufacturers.
- To compare the results with those of the propeller open water test to analyze the effect of the pod housing on the propeller open water characteristics.

2.2.2 Test conditions

The test conditions for a pod unit open water test are the same as for a conventional propeller. The tests should be conducted under the constant rate of revolutions at least at two rotation rates:

- Close to rpm of the matching propeller open water test for an analysis of the propeller-pod housing interaction.
- As high as possible rpm, high enough to minimize Reynolds scale effects (laminar flow effects); this essentially for a prediction of full scale propeller performance for the propeller designer and to assess the effects of Reynolds number variation on the pod performance.

2.2.3 Set up

The pod unit open water test is a test of the complete unit with propeller and pod housing.

A special test set-up is required for this test. The recommended test configuration is shown in Figure 4. while a photograph of such set-up is shown in Figure 5 for further information.

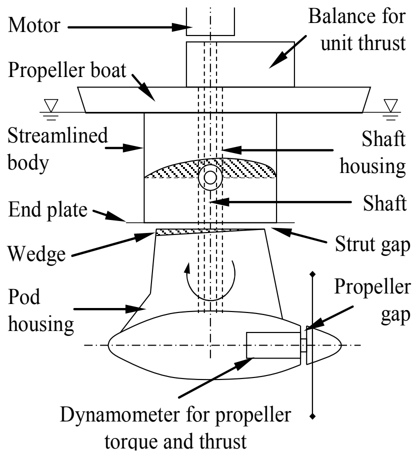


Figure 4 Typical pod unit open water test set-up

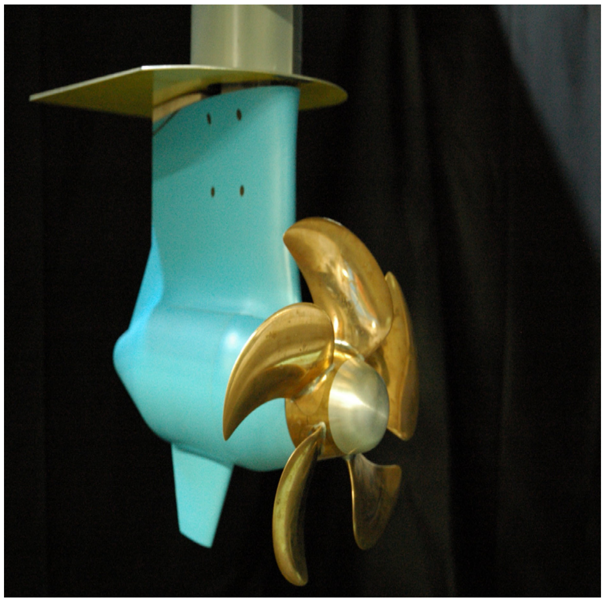


Figure 5 Typical pod unit open water test set-up

In this test set-up the propeller is driven by a motor mounted on a 2- to 6-component measuring frame fitted on the top support plate which is identified in Figure 4 with the bottom of the propeller boat. To avoid water surface effects, the propeller shaft must be immersed at least 1.5 times the propeller diameter *D*, but preferably 2*D*. It must be emphasized that the top of the strut should also be well submerged.

Shaft housing cover and end plate

The exposed part of the shaft between the top support plate and the top section of the pod strut, must be protected by means of a body,

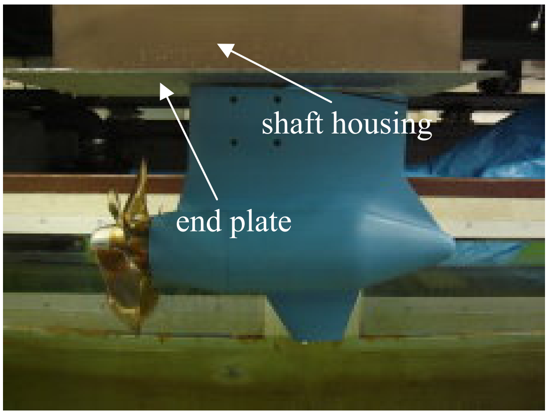


Figure 6 Shaft housing and end plate

which is described as "shaft housing" as shown in Figure 6, to prevent it creating drag itself.

This body is well streamlined and fixed to the bottom of the top support plate. A thin but sufficiently long and wide end plate is fitted horizontally to the bottom of the streamlined body, also shown in Figure 6, to prevent the induction of vertical flow components due to the difference in size between streamlined body and pod strut, which could affect the flow over the pod strut.

Top support plate

The top support plate is fitted to the towing carriage as close as possible to the water surface, with a maximum distance of 1 cm, to prevent surface wave effects.

Propeller shaft line and wedge

The propeller shaft must be set horizontal. If in this position the pod strut has an inclined top section, it is advised to make it horizontal by adding a wedge, as shown in Figure 7, to prevent an uneven strut gap which will affect the pod performance by influencing the local flow. This wedge will add some wetted surface to the pod, but it is expected that its effect on the pod resistance is much smaller than the effects of an inclined strut top section

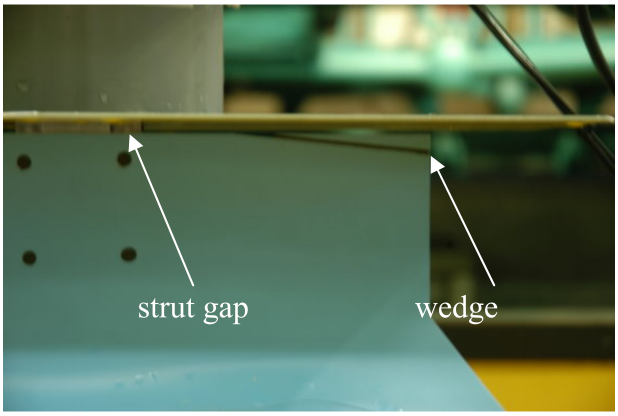


Figure 7 Strut gap and wedge

Strut gap

There is also a gap between strut top and the lower end-plate of the test set-up, as shown in Figure 7. This gap can affect the pod resistance as illustrated in the results of a puller type pod resistance tests shown in Figure 8. It can be concluded that the gap between the top of the strut and the end-plate should preferably be kept as small as possible. This is because the gap at full scale is almost zero if we manufactured scaled model – at least at the vertical shaft location where the unit is fitted into the hull. Nevertheless, a certain gap is required to allow some motion of the pod housing relative to the end plate

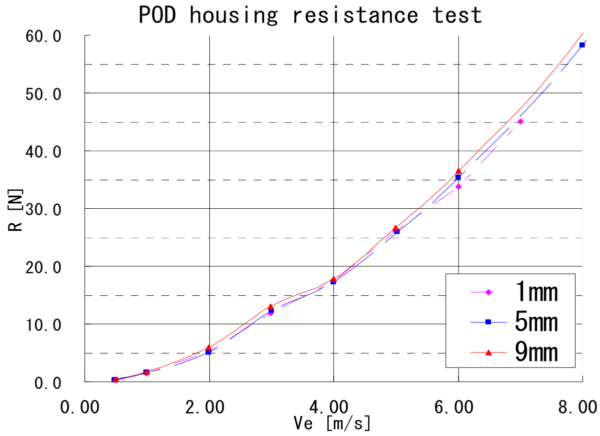


Figure.8 Pod resistance of table 4 with different strut gaps

Propeller gap

A typical view of propeller gap is shown in Figure 9. The width of the propeller gap has hardly any effect on the measured pod unit thrust, but can have a clear effect on the propeller performance. In the case of thrusters or pods that have propellers with strong conical hubs, especially in pulling units, the propeller thrust deviates quite substantially from that of similar propellers with more cylindrical hubs.

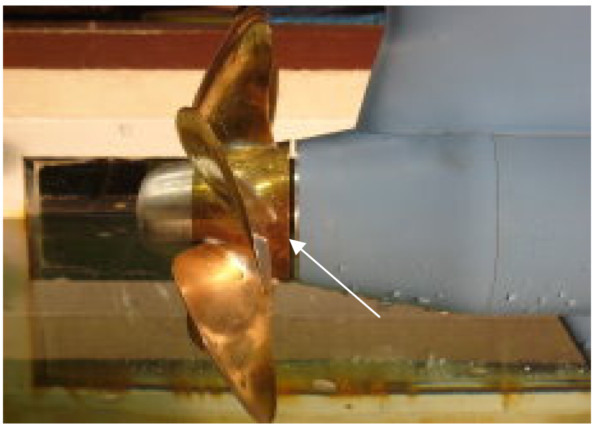


Figure 9 Propeller gap

Flow pressures in the gap cause additional forces on the propeller hub and the adjacent circular end section of the pod housing. Both forces are similar in strength but act in opposite directions, thus the propeller thrust measurement is affected, but the unit thrust measurement, containing both forces which cancel each other, is not affected. This implies that the gap width is important, but only for the determination of the performance of the propeller on the pod. Measurements by some hydrodynamic institutes have shown that differences in propeller thrust of up to 8% were found between propellers with a conical hub and with a cylindrical hub. A typical example of this effect is shown in Figure 10 by Rijsbergen and Holtrop, 2004.

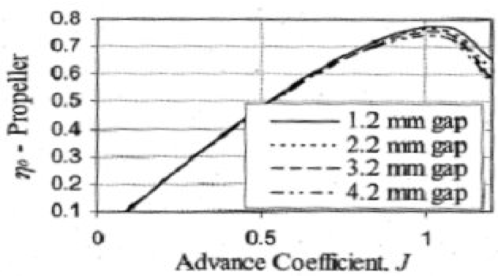


Figure10 Open water efficiencies of a pod unit based on measured propeller thrust for different propeller gap widths [HoltropRef.2]

From one of the well-known pod manufacturers it is known that most of the units use a gap width on full scale of maximum 10 mm, in order to avoid problems with cables and ropes that could get caught in the gap and could thus obstruct the pods. When scaling down this gap width, it would mean a model scale value of about 0.5 to 0.3 mm. This is not possible in model tests, which require a gap of at least l mm to avoid any possible interference between propeller hub and pod housing. Therefore recommendation will be to apply a small gap (1mm - 3mm). In particular, if a fixed aft fairing is used in the propeller open water test, it is recommended to adopt the same gap used in the propeller open water test and propulsion test to avoid uncertainty.

It is not easy to analyze the gap effect; this includes several complex phenomena including:

- difference of potential wake due to pod housing
- discontinuity effect on flow around pod housing front end
- inner pressure effect between cap and pod housing

Further investigations are necessary to understand and quantify this gap effect, as well as determining its scale effect, to be able to make corrections for it in the pod open water performance. Thrust and torque of the propeller should be measured by means of a dynamometer fitted to the propeller shaft, as close as possible to the propeller, to prevent any disturbance in the measurements from mechanical friction. The pod unit thrust T must be measured in the 2- to 6-component measuring frame on the top support plate

Turbulence stimulator

There are two kinds of Reynolds number effects regarding the pod unit open water tests. The first effect, which is associated with the propeller blades, can be assumed similar to the one experienced in propeller open water tests while the second effect, which is associated with the pod housing, can be relatively large and should be investigated before the pod unit open water test. If a resistance test of a pod unit without the effect of propeller is conducted, the use of turbulence stimulators on the pod housing is essential to avoid the low Reynolds number effect involving extensive laminar flow and even flow separation on the pod. It is believed that the magnitude of the Reynolds number effects associated with the pod housing for puller pod is much smaller compared to the pusher type pod due increased turbulence caused by the propeller flow action. Reynolds number effects on the pod housing can be neglected if the propeller Reynolds number reaches up to 5×10^5 (Also Mewis, Ref.3). Figure 11 shows typical arrangement of turbulence stimulators (artificial roughening) applied on the strut, pod body and fin components of a puller pod unit.

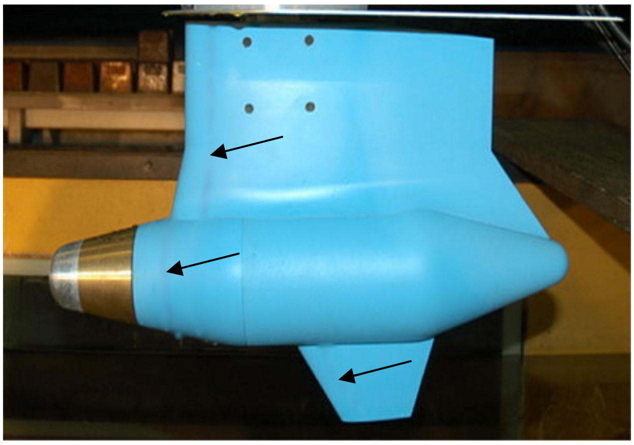


Figure 11 Typical turbulence stimulator arrangement applied to pod housing

(7) Alternative test set up

An alternative test set-up, which has been used for sometime, is to use a conventional open water drive shaft, entering a dummy pod unit and driving the propeller directly. This will also allow the measurement of propeller thrust and torque and unit thrust but the podded propulsor cannot be tested under a yaw angle. Furthermore, such an alternative pod model cannot be used in the self-propulsion tests, especially for puller-type pods, so it is advised to use the "basic" pod model as described in the next section.

Full scale correction

The podded propulsor open water test should be carried out using the same procedure as described for the propeller open water test in the previous section. The full scale correction of propeller K_T and K_Q should be done in the same manner as for a propeller alone. One approach is to use the method proposed in the ITTC'78 Extrapolation Procedure. The drag of the model pod housing should be corrected according to the methods as described in Chapter 3.2, to arrive at the full scale unit thrust T_{UNIT}, as well as the matching full scale unit efficiency.

2.3 Self propulsion test

2.3.1 Test objectives

Podded propulsor (self-) propulsion tests are required:

- to predict the ships calm water performance with the best possible accuracy
- to predict the propulsor hull interaction coefficients

2.3.2 Test conditions

After a resistance test of the ship without a pod unit (same as a conventional propeller case), it is recommended that for ships fitted with podded propulsors, self propulsion tests should be conducted with both the ship speed and the propulsor load varied independently. In addition to SFC (Skin Friction Correction) of hull surface, load correction due to pod housing drag correction (ΔT_{U}) should be considered.

2.3.3 Test set up

The self propulsion test should preferably be carried out in the following manner: the pod propellers to be driven from the top of the unit by an electromotor, through a belt drive or a geared set of a horizontal and a vertical shaft. Thrust and torque of the propeller are to be measured close to the propeller. The unit thrust is to be measured by means of an at least 2 component measuring frame at the intersection of the pod strut with the ship model, on which frame the motor is fitted.

Experience with pod testing has shown that a simple measurement of unit thrust by means of a longitudinal force transducer between vertical drive shaft and ship model does not work because there are thrust and torque effects between motor and shaft when the motor is simply fitted to the bottom of the model. A point of special concern is air leakage from the hull along the vertical drive shaft of the pod into the water. Especially for pushing units this may occur, because of the suction effect of the working propeller that creates a low pressure area around the strut. Air leakage may lead to propeller ventilation and should thus be prevented. For instance thin flexible latex hoses can be used to close off the opening between ship model hull and the tube around the drive shaft of the thruster model.

Furthermore, care is to be taken that the Reynolds number of the flow around the pod model is high enough to avoid extensive laminar flow and even flow separation on the pod unit. In general this asks for as large as possible ship and pod models. The use of turbulence tripping on the pod housings helps to locally remedy a delayed flow transition, but is mostly of interest for pushing pods. The turbulent flow from the propeller will ensure in general a good enough turbulent flow over the housing of a pulling pod .For the pod housing drag, in first instance the difference between the propeller thrust (as the propeller attached to the pod) and unit thrust can be taken.

However, as explained before, the gap between propeller hub and pod housing affects the measurement of the propeller thrust. Furthermore, scale effects are present on the measured pod housing drag and they should be corrected for as described in Chapter 3. Alternatively, the pod housing drag can be obtained through pod resistance tests (pod open water tests without propeller) and through ship model resistance tests with and without un-propelled pod, thus regarding the pod housing as an appendage, instead as a part of the propulsor. But this would mean that the effect of the working propeller on the pod housing resistance is neglected. Furthermore, the thrust deduction fraction t would relate the propeller thrust to the ship resistance and not the unit thrust and the wake fraction will be different from the one determined from an open water test on the complete podded propulsion unit.

The same applies to total propulsive efficiency, relative rotative efficiency η_R, etc.

In fact this alternative method is not recommended. This conclusion was already established by the Specialist Committee on Unconventional Propulsors in their Final Report and Recommendations to the 22nd ITTC, stating that for ships with for instance Z-drives, these propulsors should be tested as complete units and should not be broken down into tests on their components, being thruster/pod housing and propeller (ITTC, 1999).

In model tests in which the pod arrangement is optimized by systematically varying the longitudinal and transverse pod position, pod neutral steering angle and pod tilt angle, care should be taken to preserve the propeller tip-hull clearance. This applies particularly to tilt angle optimization, where the propeller tip should be kept on its location and the thruster/pod unit should be rotated about this point. The pod full-scale geometry can be modelled around standard model thruster units. The forces and moments recorded by the transducers in the measuring frame during the tests are to be processed in a standard manner. Cross-talk corrections and calibrations are linear to a high degree for the measurement set-up employed.

Prior to each propulsion test, an "in-situ" static load test should be carried out. Not only to check the calibration factors for the podded propulsor in the built-in condition, but also to serve as a check that there are no unintended contacts between the pod unit and the ship model, that will affect the propulsion measurements.

The whole procedure as described above for propulsion tests can also be applied for a special type of propulsion test: bollard pull tests. In these tests the ship speed is kept constant and only propeller load variations are carried out by varying the propeller rotation rate. The ship model is fixed to the towing carriage by means of a longitudinal force transducer. During each run the (negative) tow force on the ship model is measured, besides the standard measurements of propeller thrust, torque, rate of rotation, and pod unit thrust.

3. EXTRAPOLATION PROCEDURE

This section presents an outline extrapolation method for test on ship models equipped with podded propulsor models. It must be noted that special propulsor configurations such as pulling units behind conventional propellers in a hybrid contra-rotating combination, and podded propulsors with nozzles (rim or hub driven) are left out as future work due to their limited applications.

Power prediction procedure of a vessel with podded propulsion systems is basically the same as for a vessel with conventional propulsion system. However, there is a further complexity associated with scale effect of a podded propulsor that can be investigated under the scale (Reynolds number) effect of the propeller blades, and the scale effect of the pod housing drag.

Establishment	HSVA	MARIN	SSPA	SUMITOMO
Number of calculation zones	3(4)	3	3	3
Frictional Resistance calculation method	Schoenherr	ITTC 1957	ITTC 1957	ITTC 1957
Pressure Resistance calculation	No	form factors	form factors	form factors
Strut- pod body interaction	No	No	Yes	Yes
Inflow velocity components	Axial only	Axial only	Axial only	Axial only

Table3 A summary of details of existing semi-empirical correction methods for pod housing drag

As stated in earlier sections, while the treatment of the first effect is the same as a conventional propeller and can be corrected by the method proposed in the ITTC'78 Extrapolation Procedure, the scale effect of pod housing drag is more complex and several empirical correction methods have been presented by different establishments and these have been discussed in details by the 24th ITTC Pod Committee [Ref.1]. A summary of some details of these empirical methods is presented in Table 3.

In addition to the above empirical methods, KSRI presented another simple method using scaling factor λ(= full scale/model scale) based on CFD calculations [Ref.6].

Based upon the investigation conducted by the 24th and 25th ITTC specialist committees it is recommended that the power-speed prediction of a pod driven vessel in full-scale can be conducted using a similar procedure as in ITTC'78 extrapolation method with special care involving the podded-propulsor hull interaction and pod housing drag correction as described in the following sections.

3.1 Extrapolation method of wake fraction

The most advantageous point to regard the pod unit as a propulsor is a fact that the scale effect on the hull wake can be treated similar to the wake for conventional propellers. Moreover, it is generally recognized that the scale effect on the hull wake for a ship propelled by podded propulsor(s) is assumed to be small because of the similarity to open shaft propeller arrangements, except application to a tanker or a bulk carriers with stern bulb by which they intend to maintain course keeping ability of the vessel. Therefore the existing extrapolation methods of wake fraction such as ITTC 1978 can be applied without any modification.

3.2 Extrapolation method of pod housing drag

As stated earlier, there are several methods for pod housing drag correction and differences in these methods have been reported to be considerable (24th ITTC Pod Committee report

[Ref.1]). However further investigation of the 25th ITTC Pod Committee revealed that the effect of the differences on the final power are expected to be less than 2%

Based on this fact it is justifiable to use a simple method to predict the pod housing drag in full-scale and an associated correction procedure as part of a practical power prediction exercise. In the following a semi-empirical method for such purpose is described

The pod housing drag including the effect of propeller action can be assumed to be:

$$R_{POD} = R_{BODY} + R_{STRUT} + R_{INT} + R_{LIFT}$$

Where, R_{BODY}, R_{STRUT}, R_{INT} and R_{LIFT} are components of the resistance associated with pod body, strut, pod body-strut interference, and lift effect due to swirling flow action of the propeller, respectively.

By using the form factor approach, which has been proposed in open literature as shown in Table 3, R_{BODY} and R_{STRUT} can be represented in the following manner;

$$R_{BODY} = (1 + k_{BODY}) \times R_{FBODY}$$

$$R_{STRUT} = (1 + k_{STRUT}) \times R_{FSTRUT}$$

Where $(1+k)$ is an appropriate form factor described in Section 3.2.1 and 3.2.2, R_F is frictional resistance of the respective component

Interference drag, R_{INT} can be represented by the following semi-empirical formula [Ref 5]:

$$R_{INT} = 1/2 \times \rho \times V^2 \times t^2 \times f(t_{ROOT}/C_{ROOT}) \text{ with}$$

$$f(t_{ROOT}/C_{ROOT}) = C_{ROUND} \times (17 \times (t_{ROOT}/C_{ROOT})^2 - 0.05)$$

Where, t_{ROOT} is the maximum thickness at the strut root and C_{ROOT} is the chord length at the same section. C_{ROUND} is a correction factor for various fairing and it varies from 0.6 to 1.0.

3.2.1 k_{BODY}

There are several empirical methods for resistance prediction of three dimensional stream lined bodies such as air ships. It will be reasonable to use such methods and associated formula for predicting its resistance because the shape of a pod nacelle resembles to an air ship. One empirical formula frequently used is presented by Hoerner [Ref.5] ;

$$R_{BODY} = (1 + k_{BODY}) \times (1/2 \times C_F * \rho * V^2 * S)$$

$$k_{BODY} = 1.5 \times (D/L)^{3/2} + 7 \times (D/L)^3$$

S : Wetted surface Area (m²)

L : Pod length (m)

D : Pod diameter (m)

3.2.2 k_{STRUT}

The resistance of strut can be presented as the same manner and k_{STRUT} is also presented by a simple formula (Ref.5).

$$R_{STRUT} = (1 + k_{STRUT}) \times (1/2 \times C_F \times \rho \times V^2 \times S)$$

$$k_{STRUT} = 2 \times \delta_S + 60 \times (\delta_S)^4$$

Where, δ_S is the average thickness ratio of the strut and S is the wetted surface area of the strut.

3.2.3 Effect of propeller slip stream

There are two methods to predict axial inflow velocity which is accelerated by a propeller [Ref.1,2,3].

$V_{INFLOW} = V_A \times (1 + C_T)^{0.5}$

$V_{INFLOW} = (a \times (nP)^2 + (1-a)\times V_A^2)^{0.5}$

The first equation can be applied without any empirical factor however, it can be applied only pulling pod. On the contrary, the second equation requires the empirical factor <*a*> however, it can be applied to not only on pulling pods (a=0.8) but also on pushing pods (a =0.25).

3.3 Consideration from Pod Resistance Test Results

The pod resistance test is a resistance test of the Pod unit alone which consists of a pod body and strut(s). Figure 12 shows the results of pod resistance tests conducted by totally 7 model basins. Table 4. shows the pod model dimensions. Each model basin manufactured it's own pod according to the same drawing.

Principal dimensions of Pod Propulsor	
Length of Pod Body	0.4563 m
Diameter of Pod Body	0.1135 m
Height of Strut	0.1372 m
Chord Length of Strut	0.2672 m
Total Wetted Surface Area of Pod	0.2129 m^2

Table 4 Cooperative Research Work for Pod Resistance Tests

As shown in Figure 12, big scattering can be seen among these test results and two distinctive peculiarities are mentioned:

- Below pod advance speed 3m/s, lowest result and highest value coincide to laminar/transition calculation and turbulent calculation respectively.
- Above pod advance speed 4m/s, all results except one facility tend to converge to turbulent calculation.

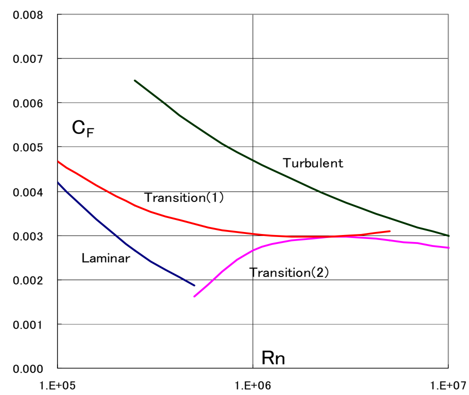


Figure 13 Frictional coefficients of laminar, transition and turbulent

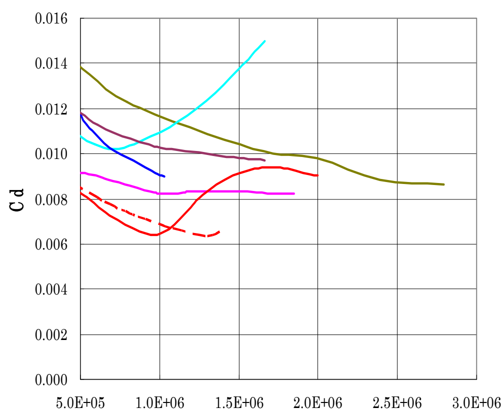


Figure 14 Drag Coefficients (Cd) measured by 7 model

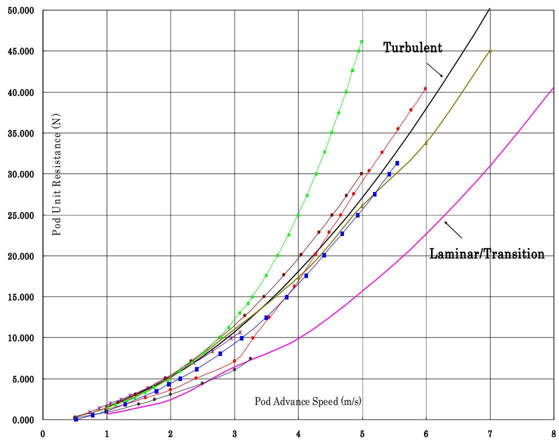


Figure 12 Results of pod resistance tests obtained from 7 model basins

Where, laminar/transition calculation and turbulent calculation are derived from the method mentioned in section 3.2. Frictional resistance coefficient curves (C_F) of each calculation are shown in Figure 13. and calculated according to following equations:

Laminar or transition

$Re < 5.25*10^4$

$$C_F = 1.327 / Re^{0.5}$$

$5.25*10^4 \leqq Re < 2.0*10^6$

$$C_F = C_F^* \ 10^{0.117* f(Re)}$$

$2.0*10^6 \leqq Re$

$$C_F = 1/(3.46 \log_{10}Re - 5.6)^2 - 1700 / Re$$

where,

$$C_F^* = 1/(3.46 \log_{10}(2.0\times10^6) - 5.6)^2 - 1700 / (2.0\times10^6)$$

$$f(Re) = \{ \log_{10}Re - \log_{10}(2.0*10^6)\}^2$$

Turbulent;

$$C_F = 0.075 / (\log_{10}Re - 2.0)^2$$

It is recommended to use laminar/transition for the outer zone of the propeller slip stream and turbulent for the inner zone.

The drag coefficients of the Pod resistance ($C_D = R_{POD}/(1/2*\rho*V^2*S)$) based on total wetted surface area (S) measured by 7 model basins are shown in Figure 14. If we compare Figure 14 with Figure 13, the following facts are self-explanatory.

- Below Reynolds number 1.0×10^6, the reason of large scatter mentioned before originates from unstable flow fields due to the transition region
- Above Reynolds number 1.5×10^6, all measured data except one data tend to converge to turbulent flow characteristics.

3.4 Full scale podded propulsor characteristics calculated by present method

As stated earlier, powering prediction of a vessel with podded propulsion system is basically the same as a conventional ship with conventional propulsion system. The difference exists only in propeller efficiency as described below:

$$\eta_D = (1 - t) / (1 - w) \times \eta_R \times \eta_0$$

$$\eta_0 = (J/2\pi) \times K_{TU} / K_Q$$

Here, K_{TU} is associated with pod unit thrust (T_U) instead of propeller thrust (T_{PROP}).

Non dimensional thrust unit coefficient and torque coefficient at full scale can be obtained by following manner;

$$K_{TU} = (K_{TU})_M + \Delta K_{TP} + \Delta K_{TU}$$
$$K_Q = (K_Q)_M + \Delta K_Q$$

Where ΔK_{TP} and ΔK_Q is scale effect on propeller blades and calculated by ITTC 1978 performance prediction method.

ΔK_{TU} is corresponding to pod housing drag correction and defined as

$$\Delta K_{TU} = \Delta R_{POD} / \rho * n^2 * D^4$$

with

$$\Delta R_{POD} = \Delta R_{BODY} + \Delta R_{STRUT} + \Delta R_{INT}$$

Here, ΔR_{BODY}, ΔR_{STRUT} and ΔR_{INT} can be represented using frictional resistance coefficients and form factors of both model scale and full scale ;

$$\Delta R_{BODY} = 1/2\rho * S_{BODY} V_{PS}^2 * (1+k_{BODY}) \{C_{FM} - C_{FS}\}$$

$$\Delta R_{STRUT} = 1/2\rho * S_{STRUT} V_{PS}^2 * (1+k_{STRUT}) \{C_{FM} - C_{FS}\}$$

As stated before, there are several pod drag correction methods as shown in Table 3. The extrapolation method presented here is compared with existing methods in the Table 5 by using obtained data from the cooperative research work mentioned section 3.3.

Table 6 shows predicted full scale housing drags based on presented method and existing methods. As shown in Table 5, the difference between model scale and full scale varies 1-3% depending on the applied method. This means the maximum deviation coming from the selected method is within 2% for the power prediction if the pod housing drag with propeller working condition shows the same tendency.

MODEL SCALE

V=3.25m/s

	Rpod(N)	R_body(N)	R_strut(N)	R_btmfin(N)	Rint_strut(N)	Rint_bfin(N)
ITTC	9.13	3.38	2.99	0.58	2.03	0.16
A	8.18	3.34	2.99	0.60	1.14	0.11
B	5.27	2.66	2.26	0.35		
C	6.45	2.37	1.64	0.27	2.03	0.16
EXPmin.	8.17					
EXPmax	13.38					

	Rpod(N)	R_body(N)	R_strut(N)	R_btmfin(N)	Rint_strut(N)	Rint_bfin(N)
ITTC	6.4%	2.4%	2.1%	0.4%	1.4%	0.1%
A	5.7%	2.3%	2.1%	0.4%	0.8%	0.1%
B	3.7%	1.9%	1.6%	0.2%	0.0%	0.0%
C	4.5%	1.7%	1.1%	0.2%	1.4%	0.1%

FULL SCALE

V=11.83m/s

	Rpod(KN)	R_body(KN)	R_strut(KN)	R_btmfin(KN)	Rint_strut(KN)	Rint_bfin(KN)
ITTC	44.63	13.16	11.24	1.99	16.94	1.30
A	46.76	13.01	11.25	2.06	18.60	1.84
B	20.04	10.17	8.34	1.52	0.00	0.00
C	34.97	14.14	11.24	1.99	7.06	0.54

	Rpod(KN)	R_body(KN)	R_strut(KN)	R_btmfin(KN)	Rint_strut(KN)	Rint_bfin(KN)
ITTC	3.8%	1.1%	1.0%	0.2%	1.5%	0.1%
A	4.0%	1.1%	1.0%	0.2%	1.6%	0.2%
B	1.7%	0.9%	0.7%	0.1%	0.0%	0.0%
C	3.0%	1.2%	1.0%	0.2%	0.6%	0.0%

Table 5 Pod housing drag calculated by present method and existing methods

3.5 Effect of propeller slip stream

The pod housing drag increases behind a propeller due to the propeller slip stream.

Consequently, the pod unit thrust will decrease as the pod housing drag increases as shown in Table 6.

If we check the ratio of housing drag coefficients of model scale and full scale defined by

$$\alpha = \frac{K_{\text{housing}}^{\text{calc,full-scale}}}{K_{\text{housing}}^{\text{calc,model}}}$$

,the present method gives 0.799(=6.5%/8.1%) .

	Tunit	Rpod
Model scale(present) N	139.6	11.4
Full Scale(direct) KN	1165.0	94.8
Full Scale(present) KN	1165.0	75.8
Ratio		0.799

	Tunit	Rpod
Model scale(present) N	139.6	8.1%
Full Scale(direct) KN	1165.0	8.1%
Full Scale(present) KN	1165.0	6.5%

Table 6 Effect of propeller on housing drag

3.6 Considerations from CFD computations

During the last decade CFD methods have been extensively applied to the simulation of propeller flows. Among others, scaling effects have been investigated for conventional and unconventional propulsors. In particular, detailed analysis of the complex flow around podded propulsors has been carried out and partly reported for computations made at model and full scale. Phenomena such as flow separation on pods and struts, propeller-housing interaction, etc have been numerically studied.

Full-scale validation data are not available for many of the outputs resulting from CFD computations due mainly to the complexity involved in the measurements. This is a problem when judging the reliability of CFD predictions. However, a careful and critical analysis of the CFD results may help to identify some flow phenomena of interest for the extrapolation.

In particular regarding R_{LIFT}, it is generally accepted that R_{LIFT} can be calculated within the framework of potential-flow theory and that the non-dimensional lifting forces at model-scale are valid at full scale. However, it should be mentioned that for struts with rounded and thick trailing edges (TE), flow separation at model scale plays an important role in the reduction of lift. CFD calculations suggest that for some applications the strut lift may be increased at full scale due to the reduction of TE separation in about 1.5% of the unit thrust (see Figure 15).

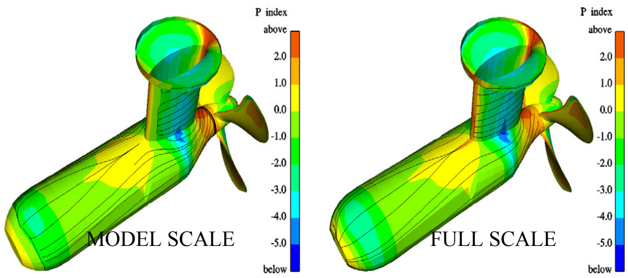


Figure15 Pressure distributions and streamlines on pod housing/strut surfaces at model and full scale (Sanchez-Caja, et al. 2003)

In the same reference the scaling of drag for a pod body with a blunt aft-end is numerically investigated. The scaling of the frictional forces seems to follow the expected trend of frictional drag reduction at full scale. However, the scaling of the pressure forces seems to contradict the trend expected in an extrapolation method based on form factors.

Within the form factor approach, the scaling of pressure drag is assumed to follow the ratio of the frictional coefficients for all types of bodies, i.e.

$$C_{TS}/C_{TM} = (1+k)C_{FS}/(1+k)C_{FM} = C_{FS}/C_{FM}$$

In principle, the form factor approach has been devised for well-streamlined bodies where ideally no separation occurs, and is supposed not to work very well for bodies with extensive separation. Blunt aft-end pods are somewhat similar to projectiles. Projectiles develop a large pressure drag at their aft-end, called '*base*' drag, which follows different scaling laws due to the generation of strong vortices on the sharp shoulders. In the past some institutions have treated this drag component in hull resistance extrapolation of small crafts abandoning the form factor scaling law. They have assumed that the form drag coefficient is the same at model and full scale (in other words, is not reduced at full scale following the ratio of the frictional coefficients).

In the referenced CFD calculation (Sanchez-Caja, et al. 2003), the pressure drag for the blunt aft-end pod body is seen not to decrease in full scale following the reduction of frictional coefficients from model to full scale, but to increase somewhat. The increase in pressure resistance predicted by CFD is in line with the trend found in experiments of increase in base drag with the Reynolds number. This result points also to the direction that it is not adequate to reduce pressure drag at full scale by the ratio of frictional coefficients for pods with blunt ends, and that it should be given to such pod shapes a special scaling treatment.

4. CFD CALCULATION EXERCISE

A calculation exercise has been made in order to apply extrapolation factors obtained by CFD to the pod case shown in Tables 4 and 7. The extrapolation procedure is explained in (Chicherin et al. 2004). A scaling factor is established as ratio of computed full scale and model housing thrust coefficients:

$$\alpha = \frac{K_{\text{housing}}^{\text{calc,full-scale}}}{K_{\text{housing}}^{\text{calc,model}}}$$

The computations were performed at KRSI and VTT following a different computational approach.

	Model scale	Full scale
Prop. Diameter	0.231	5.8
Prop. revolutions(rps)	16	2.33
advance number	0.88	0.88
Reynolds number (model)	$1.29 \cdot 10^6$	$1.14 \cdot 10^8$

Table 7. Main data for the CFD study case

KRSI used a RANS code combined with an actuator disk model for the simulation of the propeller. To close the RANS equations, KRSI code used a high-Reynolds k-epsilon turbulence model. The flow upon the entire pod housing is considered turbulent. A purpose-developed system of wall functions enabled to use a comparatively sparse mesh near the wall within a wide range of Reynolds numbers. In this exercise, the mesh consisted of 0.6 million cells. The effect of the propeller upon the pod was simulated in the RANS procedure by body forces, i.e. the solver used the actuator disk model with flow swirling. The intensity of the body forces simulating the propeller was specified based on a given propeller thrust and torque values found from open-water tests of thruster unit. This method is described in (Lobatchev, et al. 2001) and (Chicherin et al. 2004). The loading is not calculated but fixed to the value obtained from model tests.

VTT used RANS code FINFLO with a full modelling of the actual geometry of the propeller and pod housing. Chien's k-epsilon turbulence model was used in the calculation. The solution was extended to the wall, i.e. no wall functions were employed. The mesh consisted of about 6 million cells. The propeller loading was calculated as an output of the computation. The numerical approach is described in (Sanchez-Caja, et al. 2003).

A summary of the conclusions resulting from this exercise is as follows. VTT and Krylov RANS codes followed different computational approaches to the problem, and they gave also different absolute results for the pod housing drag coefficient. However, the relative differences between model versus full scale drag were represented by scaling factors of 0.655 for KSRI and 0.75 for VTT. These scaling coefficients yield a prediction of Ktunit of about 1% difference within the extrapolation of model scale test results to full scale.

For the purpose of comparing the CFD approach to the method suggested by our Committee an equivalent scaling factor was calculated for the same pod case using the recommended procedure as described in sections 3.1-3.4. A factor of 0.76 was obtained. Therefore the CFD-based scaling factor method should give results similar to the recommended simpilified procedure.

A direct comparison of CFD results was also made with model experiments and some limited full scale measurements. For the comparison the calculations made with full modeling of propeller and housing (VTT) were taken. Figure 16 shows in percentages the range of dispersion in thrust and torque coefficients and in efficiency for model scale experiments together with the CFD predictions.

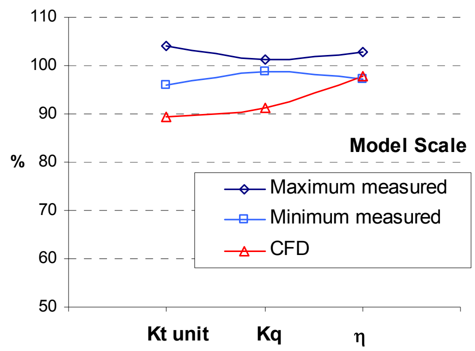


Figure 16 Range of performance coefficients from model scale experiments versus CFD predictions.

The value 100% corresponds to the mean between the maximum and minimum value obtained in the tests from the facilities participating in the experimental campaign. The computed torque and thrust were below the range in the model scale experiments. The model scale efficiency was in the lower side of the range. It should be noticed that the calculations assumed fully turbulent flow at model scale, which means larger frictional coefficients in the absence of separation.

Figure 17 shows in percentages the performance coefficients extrapolated to full scale from the experimental facilities compared to the results from the CFD computations. Full scale K_{TU} is also given. At full scale the computed thrust, and efficiency fell within the dispersion range of the predictions made by the institutions participating in the experimental campaign. The torque was somewhat smaller.

The difference in computed K_{TU} at full scale from ship measurements was 5%, which is encouraging. The mean value of the extrapolations made by the experimental facilities was about 9% above the experimental one.

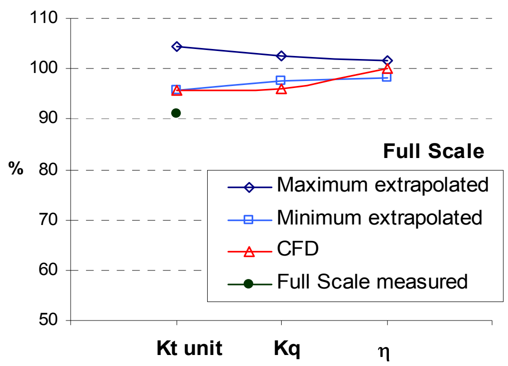


Figure 17 Range of performance coefficients extrapolated to full scale by different model basins

	Direct CFD	ITTC simplified procedure
Blades	100.0%	100.0%
Strut+ uppermost body	-4.6%	-2.7%
Pod body	-2.9%	-2.9%
Fin	-0.2%	-0.5%
TOTAL(unit thrust)	92.4%	93.9%

Table 8 Comparison of results from direct CFD and TC simplified method on pod housing drag calculations

Table 8 compares the results obtained by direct CFD simulation at full scale with those obtained following the ITTC recommended method.

Therefore the CFD based scaling factor method should give results similar to the recommended simplified procedure for pods with streamlined body. However, this is not the case for blunt pod body aft end and strut with rounded and thick trailing edge, and more detailed calculations (such as base drag approach or CFD) will be needed.

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