CHALMERS
UNIVERSITY OF TECHNOLOGY

Assessing Scale Effects on a Propeller in Uniform Inflow Condition

Downloaded from: https://research.chalmers.se, 2024-05-08 23:14 UTC

Citation for the original published paper (version of record):

Khraisat, Q., Alves Lopes, R., Persson, M. et al (2023). Assessing Scale Effects on a Propeller in Uniform Inflow Condition. NuTTS 2023 - 25th Numerical Towing Tank Symposium Proceedings

N.B. When citing this work, cite the original published paper.

research.chalmers.se offers the possibility of retrieving research publications produced at Chalmers University of Technology.
It covers all kind of research output: articles, dissertations, conference papers, reports etc. since 2004.
research.chalmers.se is administrated and maintained by Chalmers Library

(article starts on next page)

Assessing Scale Effects on a Propeller in Uniform Inflow Condition

Qais Khraisat,[*] Rui Lopes,[*] Martin Persson,[†] Marko Vikstrom,[†] and Rickard E. Bensow[*]
[*]Chalmers University of Technology, [†] Kongsberg Hydrodynamic Research Center
qais.khraisat@chalmers.se

1 Introduction

Open water testing at model scale is a universally accepted method to evaluate propeller characteristics and performance. Such tests are usually performed in towing tanks or cavitation tunnels where a model of the propeller is placed under a uniform inflow condition. However, one major drawback of such tests is the inability to satisfy the Reynolds number similarity between model and full scales. As a result, differences in the development of the boundary layer and the laminar-turbulent transition appear between the two scales. To overcome this scaling issue, the obtained propeller data from the tests are usually corrected and extrapolated to full-scale condition. Several existing extrapolation procedures have been developed as summarized in Helma *et al.* (2018), and it is shown that the predicted results depend on the chosen scaling method. One of the most common scaling procedures is the 1978 ITTC Performance Prediction Method. Although this procedure is widely used, it was developed based on statistical data from conventional open propellers which limits its scope of applicability.

With the development of Computational Fluid Dynamics (CFD) tools, it is possible to simulate cases in full scale conditions and avoid the scaling hurdle altogether. This paper aims at studying the scale effects of a propeller in uniform open water condition. Five different scales are investigated from low Reynolds numbers in the range of model scale testing ($\approx 10^5$) to high Reynolds numbers ($\approx 10^7$) corresponding to a full scale condition. Another objective of this study is to evaluate how the ITTC 78 scaling procedure performs in cases with varying scaling ratios. The numerical results will be compared with model scale experimental measurements performed at the Kongsberg Hydrodynamic Research Center.

2 Test Case

For this work, the propeller geometry is designed for a chemical tanker and is described as a moderately skewed controllable pitch 4-bladed propeller. In the numerical set-up, the blades are mounted on a simplified cigar-shaped hub as shown in Figure 1 (left), and the propeller is then placed in a cylindrical-shaped computational domain shown in Figure 1 (right). The domain length and cross-section dimensions are based on the propeller's geometrical scale and they are 40 and 20 times larger than the propeller diameter, respectively.

To obtain a comprehensive evaluation of the scale effects, five different cases with various Reynolds numbers (Re) were simulated. The five cases include the experimentally tested model scale of the propeller, its full scale counterpart, and three intermediate scales. The Reynolds number is calculated as:

$$Re = \frac{c\sqrt{V_A^2 + (0.75\pi nD)^2}}{\nu}, \tag{1}$$

where c is the propeller chord length at 0.75 of the propeller radius, V_A is the advance velocity, n is the rotational velocity, and ν is the water kinematic viscosity. The range of Re for the different cases is shown in Table 1. Several advance ratios J for the propeller ranging from heavily loaded to lightly loaded conditions are investigated. Therefore, the Reynolds number will slightly change depending on J. It is worth noting that the change in J was achieved by following the experimental procedure of adjusting V_A, while keeping a fixed n.

3 Numerical Method

All simulations were performed using the commercial software package Simcenter STAR-CCM+ 2022.1.1. The boundary conditions are set as shown in Figure 1 with a constant magnitude velocity inlet, a pressure

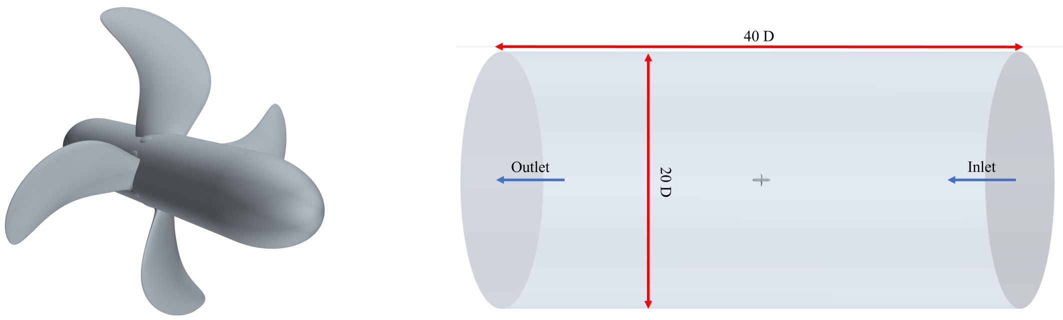

Fig. 1: Propeller Geometry (left), Computational Domain (right)

Table 1: Range for Reynolds Numbers for Simulated Test Cases

Model scale	Inter scale 1	Inter scale 2	Inter scale 3	Full scale
$\approx 7.5 \times 10^5$	$\approx 1.85 \times 10^6$	$\approx 4.3 \times 10^6$	$\approx 1.0 \times 10^7$	$\approx 2.4 \times 10^7$

outlet, and a symmetry plane on the other cylindrical surface. The propeller surface is modeled with a smooth no-slip wall boundary condition. It was found from other simulation cases that roughness plays a role in the propeller performance and the flow structure on the blade. However, its effects will not be considered in the scope of this paper.

The steady-state Reynolds-averaged Navier-Stokes equations approach is used to run the simulations, and turbulence is modeled using the $k - \omega$ Shear Stress Transport (SST) model as referenced in Menter et al. (2003). Turbulence intensity and viscosity ratio are set at 1% and 10, respectively. To assess the influence of laminar to turbulence transition in the boundary layer, the $k - \omega$ SST-γ transition model will be employed for all cases and compared with the results of the turbulence model. The model solves an additional transport equation for the intermittency to predict the onset of transition as outlined in Menter et al. (2015). In 'fully' turbulent cases where $Re \approx 10^7$, the influence of transition is negligible; however, it will be interesting to evaluate the Re range at which laminar flow still has a notable presence and influence on the propeller performance.

Since the propeller is placed under a uniform inflow condition, it is possible to run the simulation with the Moving Reference Frame method. With this modeling approach, the transient case is transformed into a steady-state problem and gives a time-averaged solution of the flow field reducing the computational cost. Also, to avoid interpolation errors at interfaces, the entire domain is modeled to be 'rotating'.

The domain is discretized with the built-in advancing layer mesher which generates layers of prismatic cells near the walls and polyhedral cells for the bulk volume of the domain as shown in Figure 2. A grid sensitivity study is performed for each of the different cases. One example is provided in Table 2 for the model scale case grid study. The grid refinement is performed following the outlined procedure by Crepier (2017) to generate as geometrically similar grids as possible. A similar convergence trend is obtained for the components of K_T and K_Q in the other scaled cases as well.

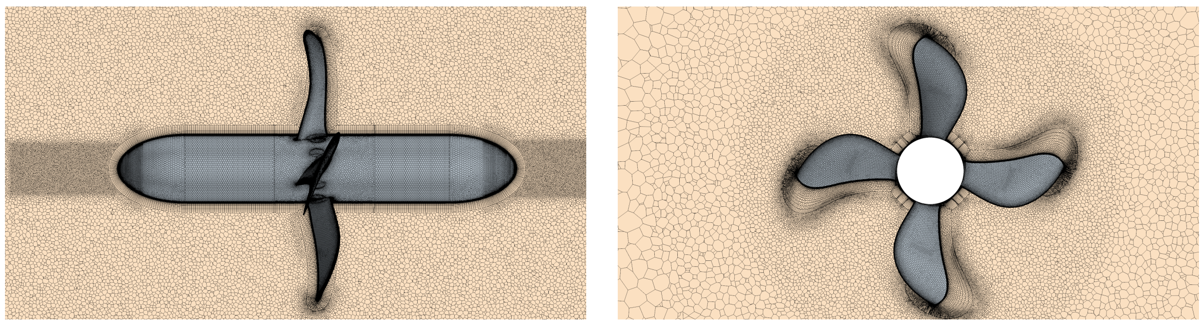

Fig. 2: Model Scale Grid, G3

Table 2: Grid Study, Model Scale J=0.711

	G1	**G2**	**G3**	**G4**	**G5**
Cell Count (in millions)	2.73	7.19	14.1	24.4	38.6
Mean y^+ (Blade)	1.23	0.81	0.64	0.53	0.36
K_T	0.1577	0.1564	0.1553	0.1546	0.1540
$10K_Q$	0.2671	0.2644	0.2621	0.2606	0.2596
η_o	66.78%	66.91%	67.03%	67.10%	67.09%

The chosen grids to perform further analysis on the different scales are summarized in Table 3. In all the cases, the boundary layer is reasonably well resolved with the non-dimensional mean $y^+ < 1$ on the blades and hub. The growth/expansion ratio of the prismatic layers, $r = 1.18$ is the same across the different scales. However, the total number of layers differs depending on the scale ratio.

Table 3: Overview of Grids for Different Scales, J=0.711

	Cell count (in millions)	Mean y^+ (Blade)	Number of prismatic layers
Model scale	14.1	0.64	40
Intermediate scale 1	13.7	0.65	40
Intermediate scale 2	14.4	0.67	44
Intermediate scale 3	15.1	0.68	48
Full scale	15.9	0.70	52

4 Results

4.1 Influence of Transition Modeling and Comparison with Experiments

As mentioned previously, model scale experimental measurements were conducted at the Kongsberg Hydrodynamic Research Center. There are two main differences between the numerical and experimental setups. First, the domain size in the numerical simulations is not a representation of the test section in the experiments. The second difference comes from the simplification of the hub geometry in the computational domain as shown in Figure 1.

Figure 3 shows a comparison between experimental and numerical results of the propeller performance at varying advance ratios. The left side of the figure shows the results of the $k-\omega$ SST turbulence model, while the right one shows the results with the $k-\omega$ SST-γ transition model. Analyzing the data of K_T and K_Q at model scale, a general underprediction relative to the experiments is obtained by the $k-\omega$ SST model. The relative difference changes depending on the loading condition of the propeller, and it varies from $\approx -3\%$ to $\approx -32\%$ for K_T. A similar range of relative underprediction is observed for K_Q as well.

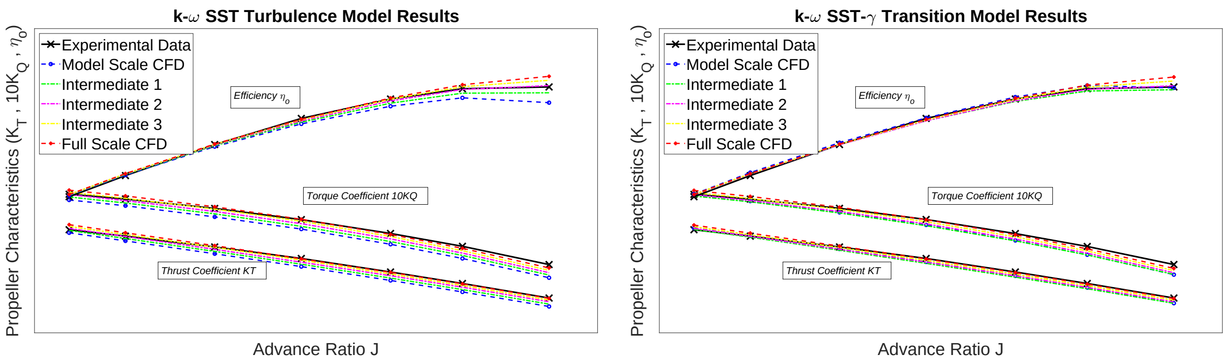

Fig. 3: Propeller Open Water Curve

On the other hand, with the introduction of the transition model, the results are greatly improved for all loading conditions in comparison with the $k-\omega$ SST model. The relative differences of K_T and

$10K_Q$ to the experiments have now dropped within the range of $\approx 0.4\%$ and $\approx 15\%$. This is attributed to the operation of the propeller at a relatively low Reynolds number, at which transition influences the flow field on the blade. For instance, Figure 4 shows a comparison of the skin friction coefficient C_F and limiting streamlines on the blade suction side at a moderate/low loading condition. The top row shows the predicted results by the $k-\omega$ SST model, while the bottom one is when also using the transition model. Looking at the model scale case, two main differences are apparent between the $k-\omega$ SST and $k-\omega$ SST-γ models. First, the transition model predicts laminar flow on the blade surface as evident by the low friction coefficient and change in flow streamline direction relative to the $k-\omega$ SST model. Second, the $k-\omega$ SST-γ transition model predicts a separating flow toward the trailing edge of the blade. This separation behavior is predicted by the $k-\omega$ SST model but is not as pronounced and appears to occur closer to the trailing edge. As a result, the pressure distribution on the pressure and suction sides of the blade is also influenced as evident by the pressure coefficient plot shown in Figure 5. The largest difference in the pressure distribution happens just after 0.8 of the chord length which is the region the transition model predicts flow separation to take place. Such differences between the $k-\omega$ SST and transition model explain the different predictions of the propeller performance in the open water curve in Figure 3.

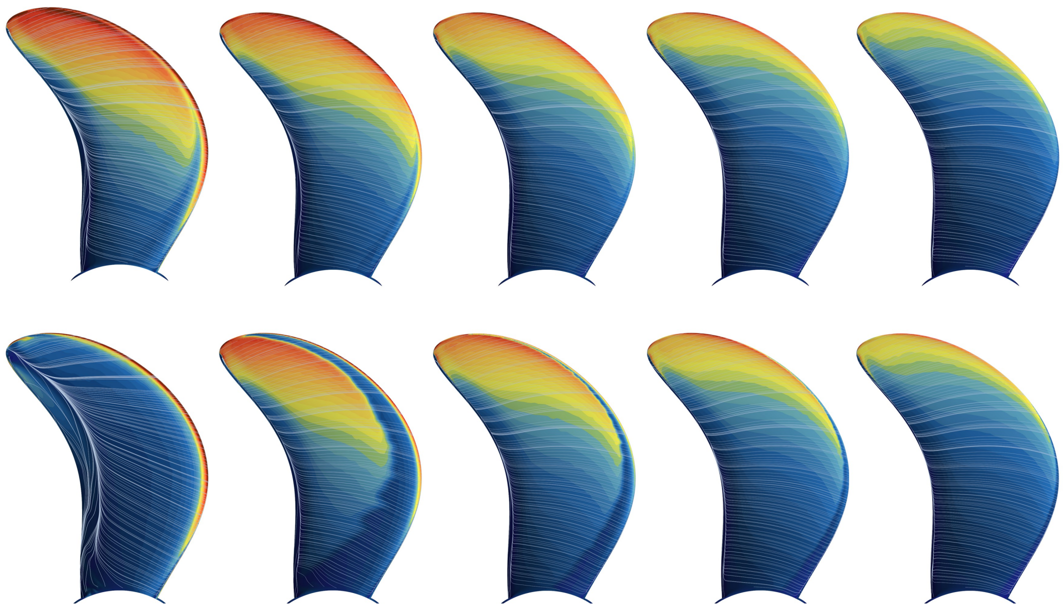

Fig. 4: Skin Friction Coefficient
(top: $k-\omega$ SST model ; bottom: $k-\omega$ SST-γ transition model)

Considering the propeller performance for the other intermediate scales, the numerical data indicate an increase in K_T and K_Q as the Reynolds number increases. In addition, the influence of the transition model becomes less pronounced for higher scales. At intermediate scale 1 ($Re \approx 1.85\times10^6$), the transition model predicts an increase in the thrust and torque coefficients relative to the $k-\omega$ SST model by 2.5% or less, depending on the loading condition. This again is explained with the same logic of how the transition model influences the flow field as Figure 4 shows, and hence the pressure distribution on the blade. The transition region at intermediate scale 1 is clear where the skin friction suddenly increases and the streamlines change direction. Making the same observation on intermediate scale 2 or above, the transition region moves closer to the leading edge depending on the local Reynolds number. For example, transition is still present even for full scale at low radial locations where the local Reynolds number is relatively low. However, this does not influence the overall performance. The predicted thrust and torque by the transition model simulations deviates with less than 1% relative to the $k-\omega$ SST model, even when the propeller is lightly loaded. Based on this analysis, it seems that when operating in Reynolds numbers in the range of 4×10^6 or higher, the inclusion of a transition model will not change the predicted propeller performance dramatically.

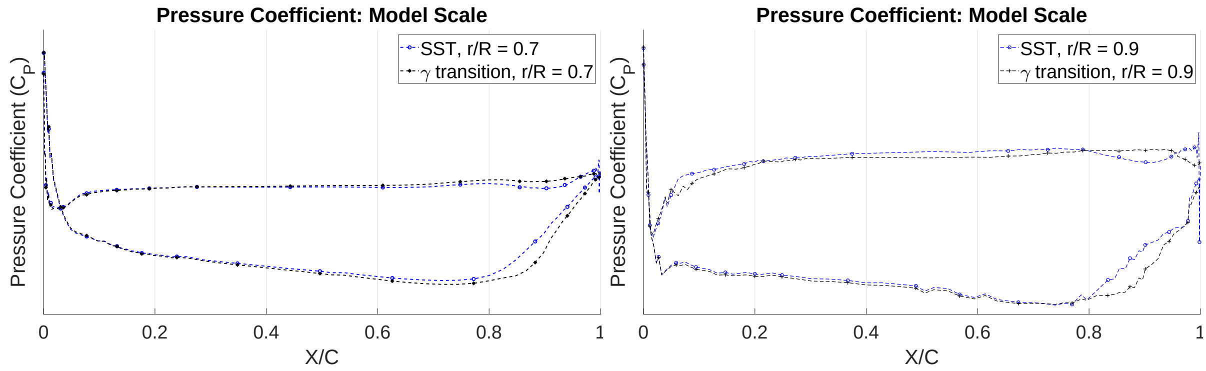

Fig. 5: Pressure Coefficient at Model Scale: $k - \omega$ SST vs $k - \omega$ SST-γ transition model

4.2 ITTC Scaling and Comparison with CFD

With the ITTC method being the most widely used scaling procedure, the purpose of this section is to evaluate how it performs for the different scales. The procedure attempts to correct the thrust and torque coefficients to get a prediction for the propeller performance at full scale. The correction for the change in the scaled thrust and torque coefficients ($\Delta K_T, \Delta K_Q$) is mainly dependent on the drag coefficient through,

$$C_{DM} = 2\left(1 + 2\frac{t}{c}\right)\left(\frac{0.044}{Re_c^{\frac{1}{6}}} - \frac{5}{Re_c^{\frac{2}{3}}}\right) \tag{2}$$

$$C_{DS} = 2\left(1 + 2\frac{t}{c}\right)\left(1.89 + 1.62\log\frac{c}{k_P}\right)^{-2.5} \tag{3}$$

where t is the maximum blade thickness, c is the chord length, and k_P is the roughness height which is set to 30×10^{-6} m. For more details on the method, please refer to the ITTC 78 scaling procedure document (ITTC 78, 2017). Here, the correction for C_{DM} accounts for the Reynolds number, while C_{DS} accounts for the surface roughness condition at full scale. Therefore, one is led to believe that the scaling procedure only accounts for the friction component of the drag and disregards the pressure component.

Tables 4,5, and 6 provide a summary of the predicted change in the scaled thrust and torque coefficients of the $k - \omega$ SST data for model and intermediate scales. It should be noted that similar trends were obtained for the results of the transition model, but are not shown in this paper. Looking at the predicted change in K_T shown in Table 4, the ITTC provides contradicting results for the different scales. For example, scaling the model scale data indicates for a small increase within the range of $\approx 0.05\%$ to $\approx 0.19\%$. On the other hand, the scaling procedure predicts a decrease in thrust coefficient for the intermediate scales at the higher Reynolds numbers. Not only does this contradict the scaled model scale data, but it also contradicts the full-scale CFD data. The numerical results show that as the Reynolds number increases, K_T increases as evident in Figure 3. In addition, the scaled torque coefficient results shown in Table 5 reveal contradicting results yet again. While the scaling procedure predicts a drop in K_Q for the model scale, it predicts an increase for the intermediate scales. As a result, such discrepancies will have an influence on the predicted scaled efficiency as Table 6 shows. One additional observation of the ITTC results is that it is too conservative relative to numerical data. For example, Figure 6 demonstrates how the ITTC underpredicts the propeller performance relative to full-scale CFD. The relative differences between the two are in the range of -6% to -19% for thrust and torque coefficients. Such underprediction is attributed to the dominant pressure component of K_T and K_Q which is not considered with the ITTC method.

To summarize, based on the obtained results, it seems that the ITTC scaling method provides inconsistent prediction depending on the Reynolds number. This could be attributed to the reason that it only considers the friction component of drag in its procedure. While the friction component is important, the total K_T and K_Q is dominated by the pressure component. Therefore, with such limitation, the applicability of the ITTC method for this specific case is questionable. Further study on a more classical propeller is needed to confirm such a conclusion.

Table 4: ITTC Predicted $\%K_T$

J	MS	Int. 1	Int. 2	Int. 3
1	0.188%	-0.079%	-0.325%	-0.536%
2	0.123%	-0.050%	-0.219%	-0.370%
3	0.098%	-0.038%	-0.173%	-0.296%
4	0.079%	-0.029%	-0.138%	-0.239%
5	0.067%	-0.023%	-0.116%	-0.202%
6	0.058%	-0.019%	-0.100%	-0.175%
7	0.054%	-0.017%	-0.092%	-0.161%

Table 5: ITTC Predicted $\%K_Q$

J	MS	Int. 1	Int. 2	Int. 3
1	-0.766%	0.337%	1.425%	2.400%
2	-0.577%	0.238%	1.063%	1.871%
3	-0.493%	0.193%	0.895%	1.544%
4	-0.428%	0.158%	0.763%	1.327%
5	-0.388%	0.135%	0.679%	1.189%
6	-0.359%	0.119%	0.619%	1.089%
7	-0.344%	0.111%	0.590%	1.040%

Table 6: ITTC Predicted $\%\eta_o$

J	MS	Int. 1	Int. 2	Int. 3
1	0.961%	-0.349%	-1.462%	-2.435%
2	0.704%	-0.246%	-1.090%	-1.849%
3	0.593%	-0.199%	-0.917%	-1.571%
4	0.509%	-0.162%	-0.782%	-1.351%
5	0.456%	-0.139%	-0.695%	-1.210%
6	0.418%	-0.122%	-0.632%	-1.107%
7	0.400%	-0.114%	-0.602%	-1.057%

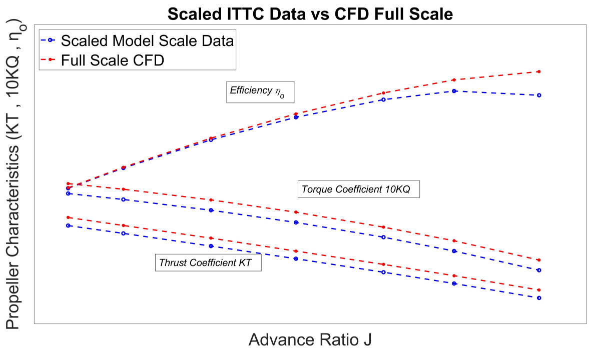

Fig. 6: Scaled ITTC vs Full Scale CFD

5 Conclusion and Future Work

After a numerical study on the scale effects of a propeller in open water condition, two main conclusions are made. First, the use of a transition model improves the results of predicted propeller characteristics depending on the operating Reynolds number. Second, the ITTC scaling method is found to be inconsistent for this propeller geometry since it only considers the friction component in the scaling procedure. Further work on roughness effects is needed to confirm this finding as it influences the friction component. Also, similar work is needed on a more classical propeller to obtain a better understanding of the ITTC scaling performance.

Acknowledgements

This project is co-funded by Kongsberg and Lighthouse-Swedish Maritime Competence Centre.
We thank Chalmers Centre for Computational Science and Engineering for providing the computational resources to run the simulations.

References

S. Helma, H. Streckwall, and J. Richter (2018). The effect of propeller scaling methodology on the performance prediction. *Journal of Marine Science and Engineering*, **6**(2), pp.60.

1978 ITTC Performance Prediction Method (2017). ITTC Quality System Manual, Recommended Procedures and Guidelines.

P. Crepier (2017). Ship Resistance Prediction: Verification and Validation Exercise on Unstructured Grids. Proceedings of MARINE 2017, Nantes, France.

F.R. Menter, M. Kuntz, and R. Langtry (2003). Ten years of industrial experience with the SST turbulence model. *Turbulence, heat and mass transfer*, **4**(1), pp. 625-632.

F. R. Menter, P. E. Smirnov, T. Liu, and R. Avancha (2015). A One-Equation Local Correlation-Based Transition Model. Springer, *Flow Turbulence Combustion* **95**, pp. 583-619.