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BETTER SHIPS, BLUE OCEANS

A Numerical Study on Model Propeller Performance Prediction Including Transitional and Passively Controlled Boundary Layer Considerations

Maarten Kerkvliet, João Baltazar, Bart Schuiling & Luís Eça

Introduction

- Laminar-Turbulent transition plays an important role in model tests and strongly depends on Reynolds number and propeller design

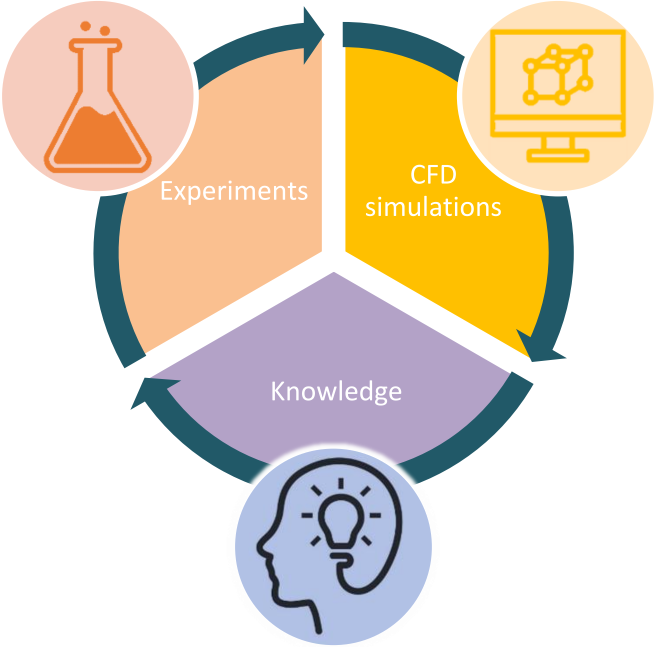
- The experimental paint-test procedure to visualise the propeller boundary layer flow offers the opportunity for numerical validation

- Can we enhance the procedures for extrapolating model-scale results using Computational Fluid Dynamics (CFD)?

Schuiling, Kerkvliet & Rijpkema, *An Experimental Study on Flow Visualisation and Passive Control of Model Propeller Boundary Layers*, SMP'24, Berlin, Germany, 2024

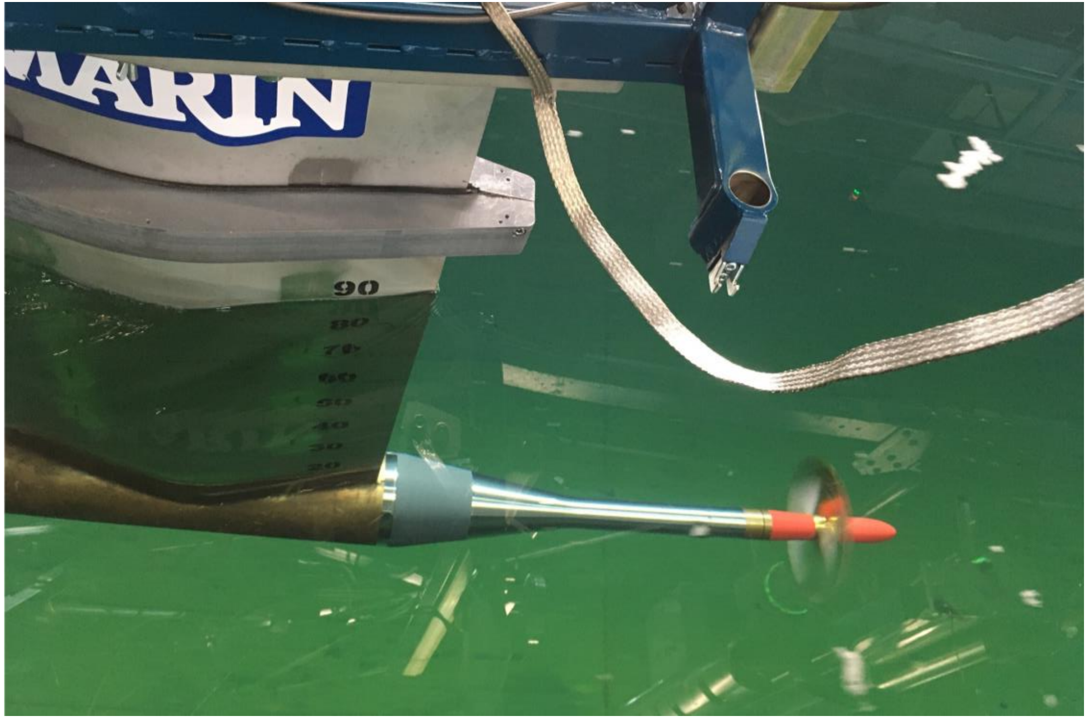
Research objectives

- Improve confidence in CFD prediction at model-scale
- Improve propeller performance prediction for full-scale conditions using CFD
- Ultimately, we want to move towards a reliable extrapolation procedure by using model-scale data and full-scale CFD



From experimental to numerical setup

- Experimental open-water setup
- Focus on the flow problem and ignore secondary issues of lesser importance



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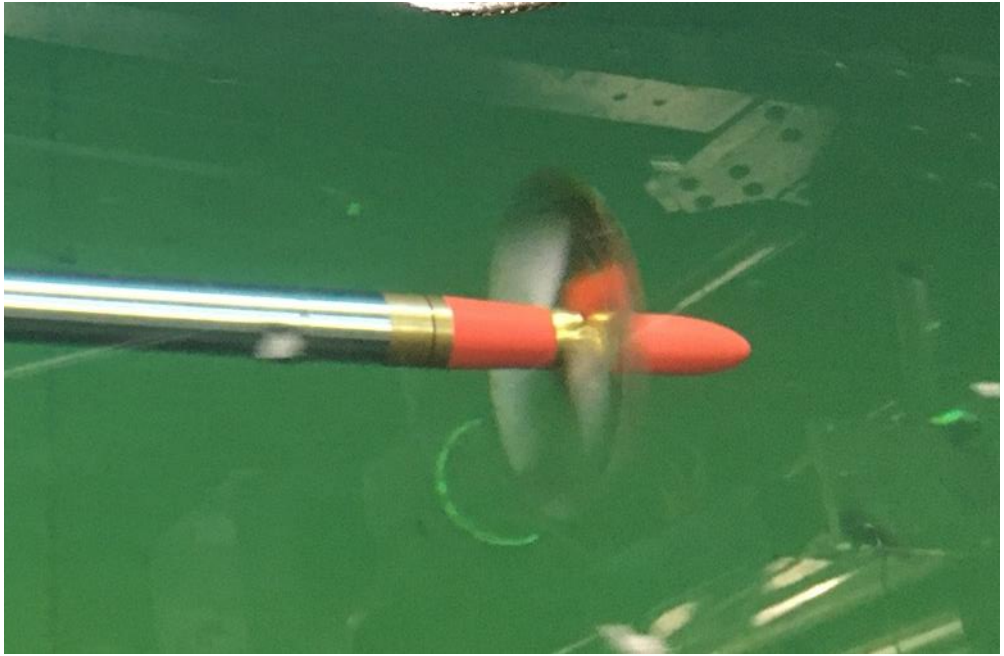
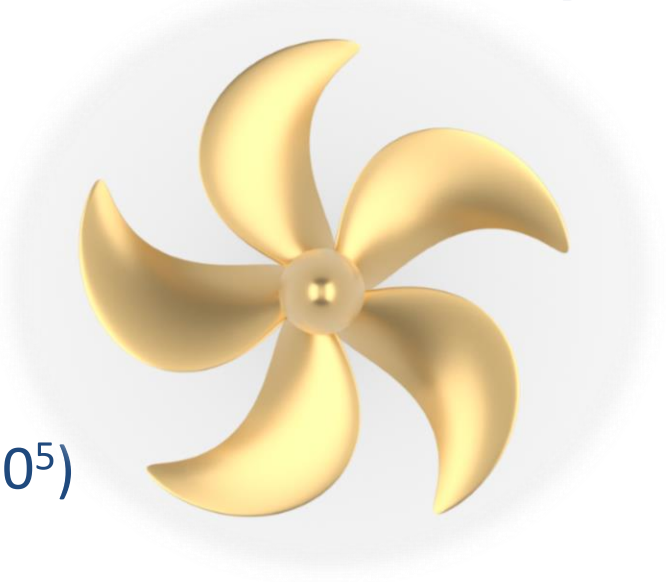


Propeller test case

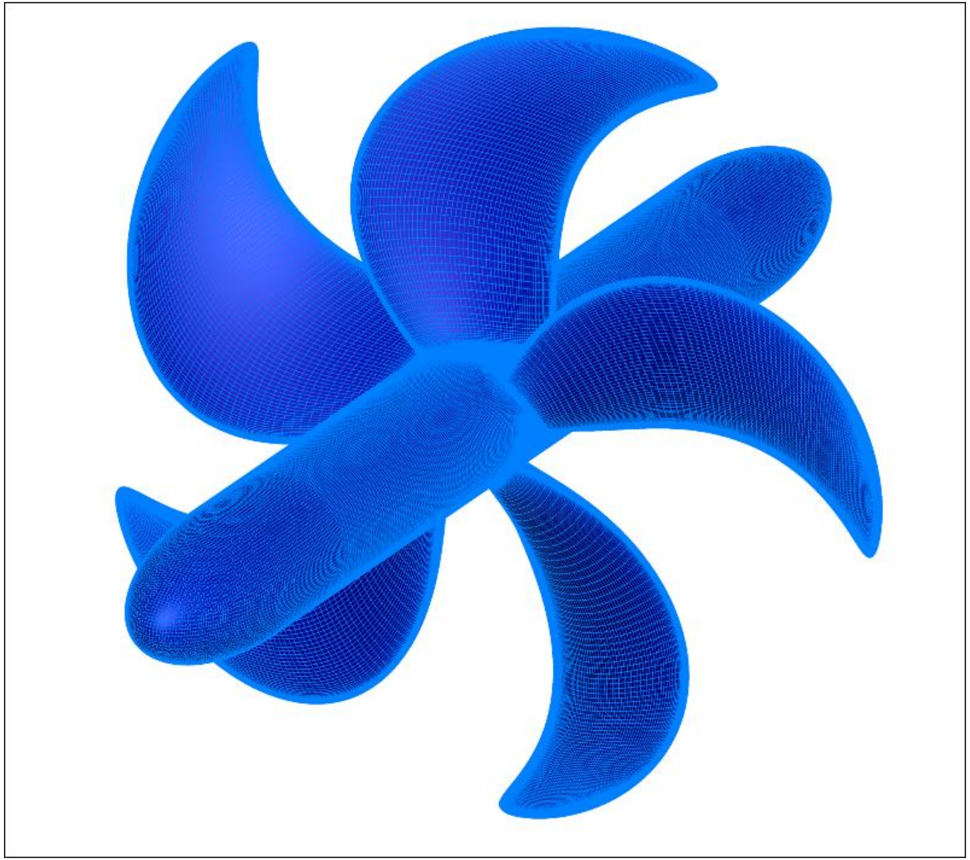
- Modern designed MARIN stock propeller
- Tested in open-water conditions
- 400 rpm ($Re = 3.5 \cdot 10^5$) & 800 rpm ($Re = 7 \cdot 10^5$)



Diameter	D	300 mm
Number of blades	Z	5
Chord at 0.7R	$C_{0.7R}/D$	0.279
Pitch at 0.7R	$P_{0.7R}/D$	1.045
Expanded Area Ratio	A_e/A_o	0.636

From experimental to numerical setup

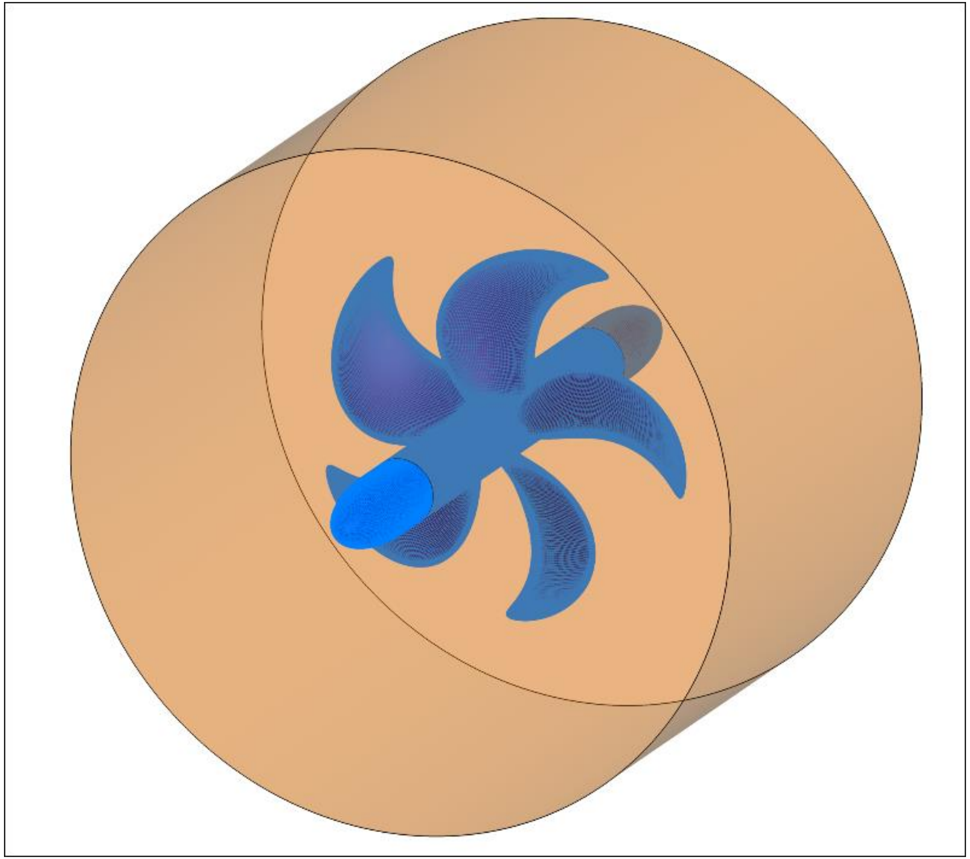
- Discretize the geometry surface by small elements



From experimental to numerical setup

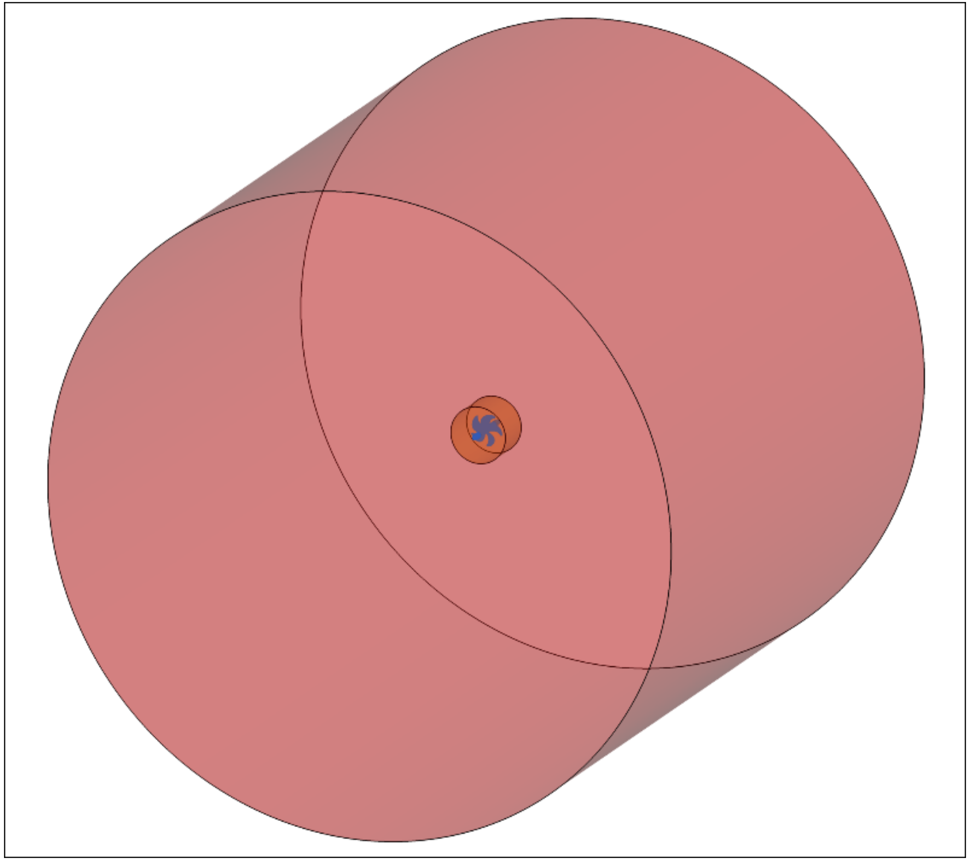
- Discretize the geometry surface by small elements

- Generate dense and high-quality (hexahedral) volume cells around the propeller



From experimental to numerical setup

- Discretize the geometry surface by small elements
- Generate dense and high-quality (hexahedral) volume cells around the propeller
- Expand towards the far field domain to avoid unintended influences of boundary conditions



Numerical setup

- CFD solver ReFRESCO
  - Developed at MARIN in collaboration with several universities and partners
  - It solves (un)steady (in)compressible viscous flows based on the RANS equations, complemented with turbulence models, cavitation models and volume-fraction transport equations for different phases
  - Many more details of current code: www.marin.nl

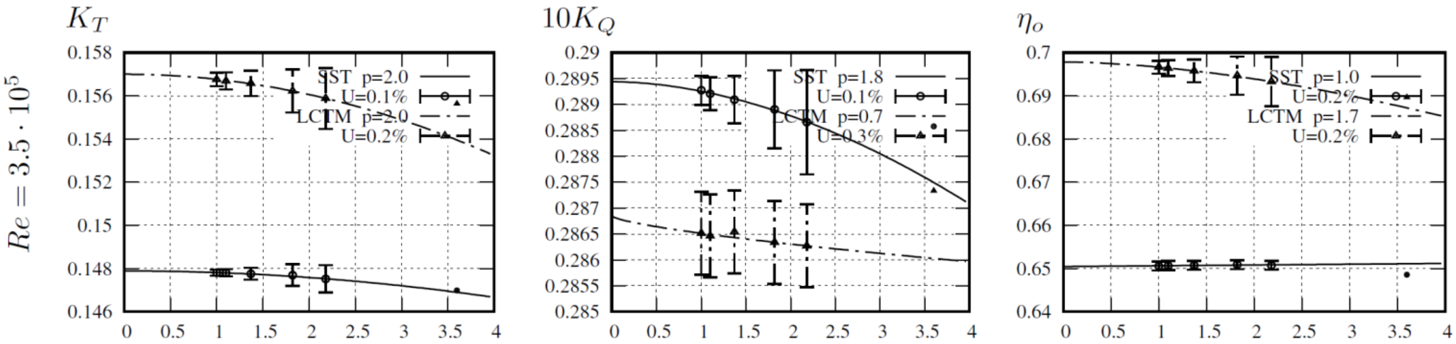
- Turbulence and transition model
  - k-ω Shear Stress Transport (SST) model
  - γ-Re_θ Local Correlation Transport Model (LCTM)

- Control of turbulence decay from the domain inlet (only for LCTM)
  - Solve turbulence transport equations without the effect of the dissipation term, up to one propeller radius in front of the propeller centerline

Verification and validation

- The choice of model depends on the specific problem, available resources, and desired accuracy

- To achieve a balance between accuracy and computational efficiency model verification is of major importance



Grid refinement ratio

Verification and validation

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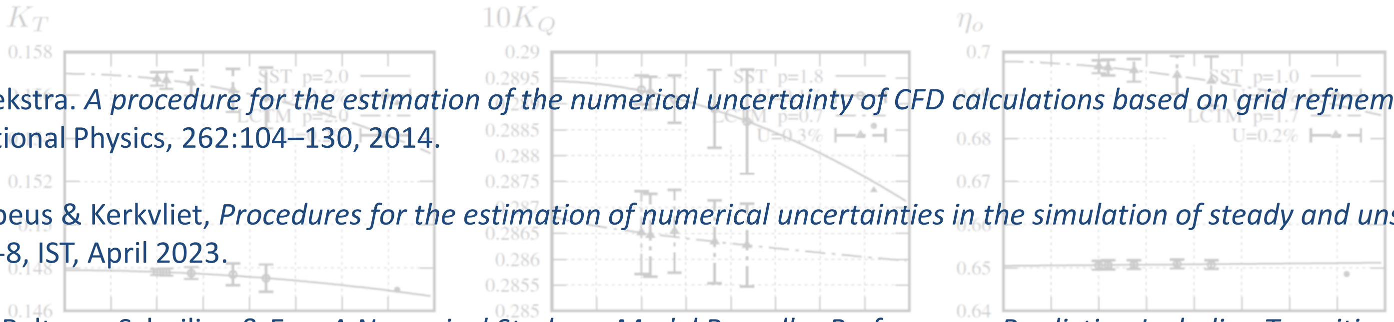


Eça & Hoekstra. *A procedure for the estimation of the numerical uncertainty of CFD calculations based on grid refinement studies*. Journal of Computational Physics, 262:104–130, 2014.

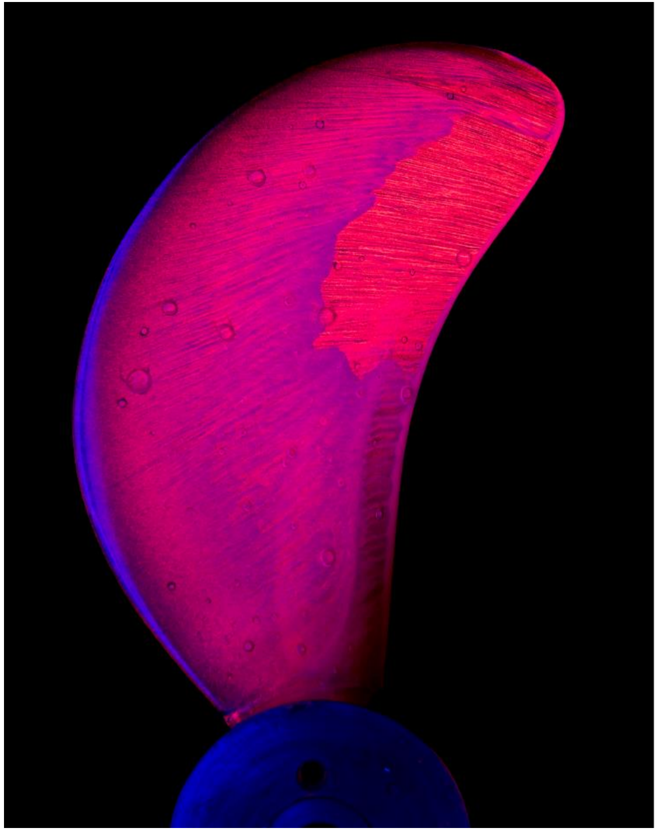
Eça, Toxopeus & Kerkvliet, *Procedures for the estimation of numerical uncertainties in the simulation of steady and unsteady flows*. Technical Report M-8, IST, April 2023.

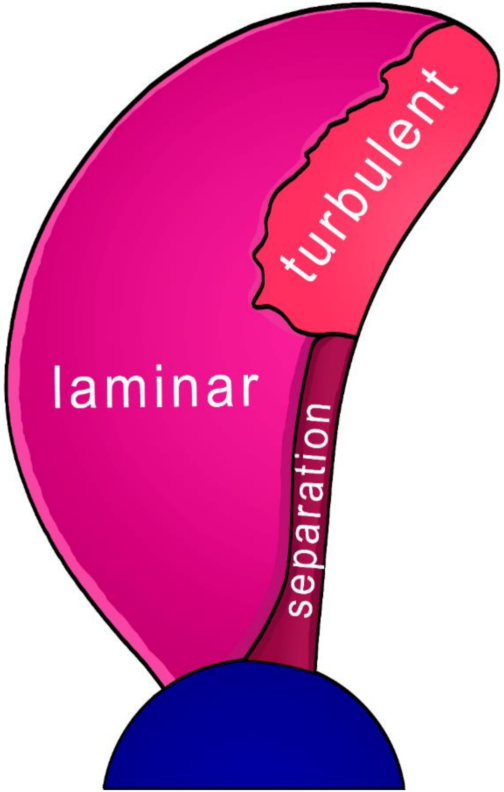
Kerkvliet, Baltazar, Schuiling & Eça, *A Numerical Study on Model Propeller Performance Prediction Including Transitional and Passively Controlled Boundary Layer Considerations*, SMP'24, Berlin, Germany, 2024.

Model-scale problem

- Boundary layer flow transition and flow separation occurs at model scale conditions

- This complicates the extrapolation process to full-scale propeller performance prediction





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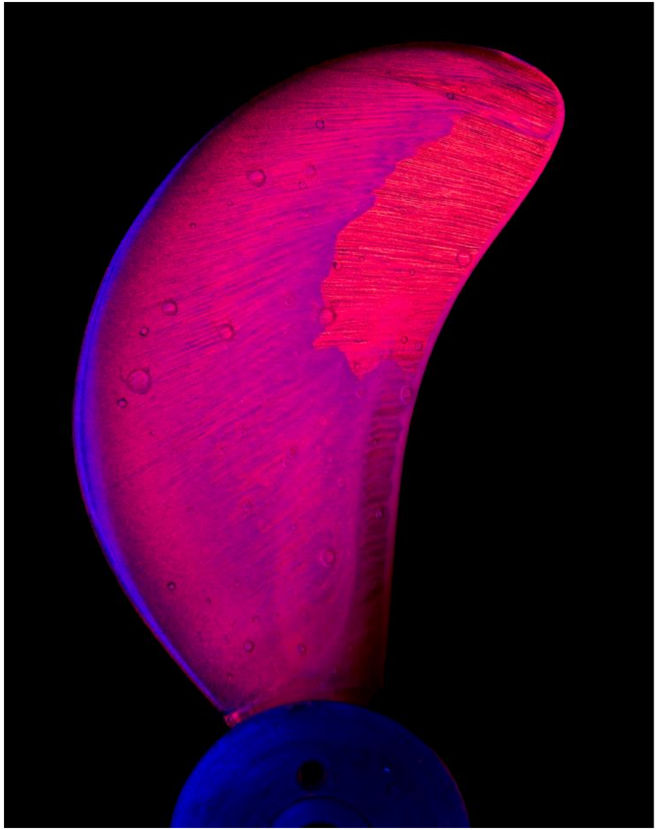
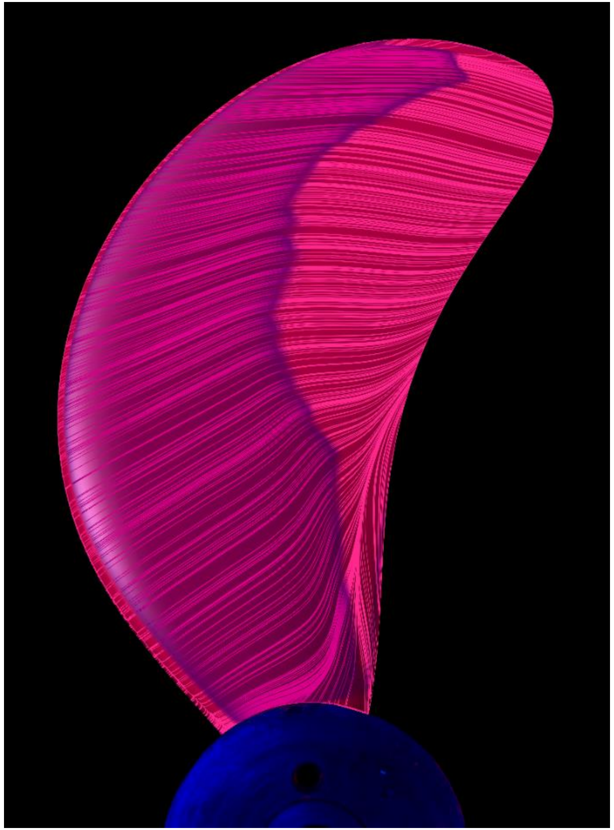


Experiment



CFD

CFD approach including transition modelling

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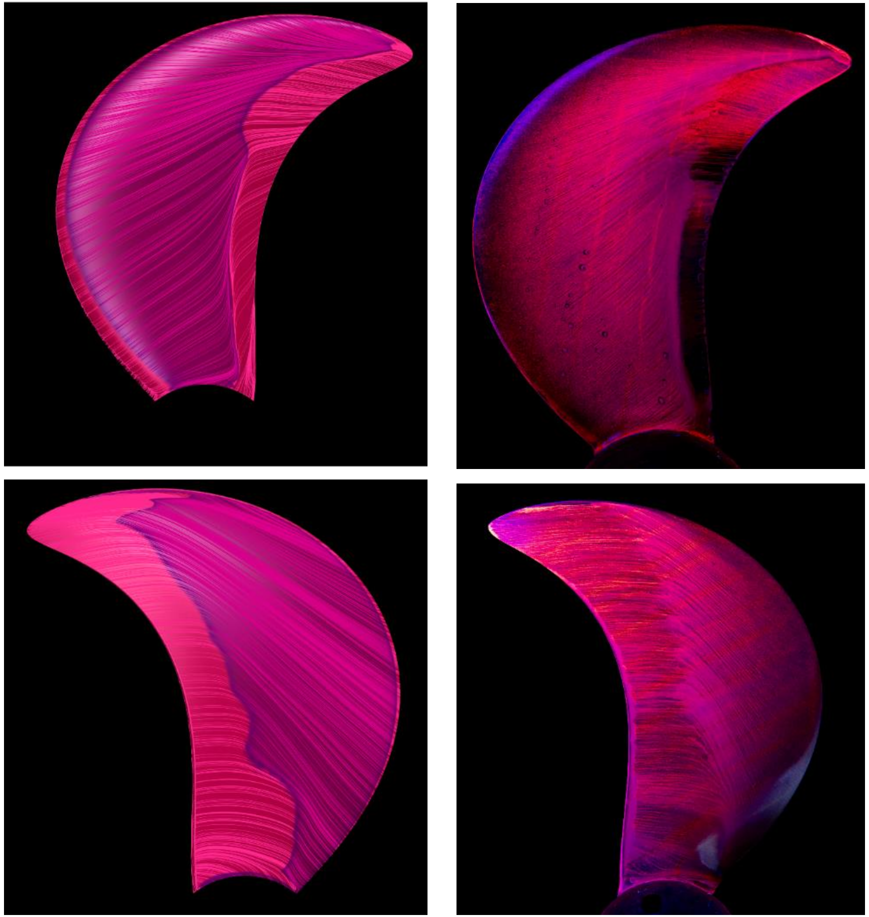
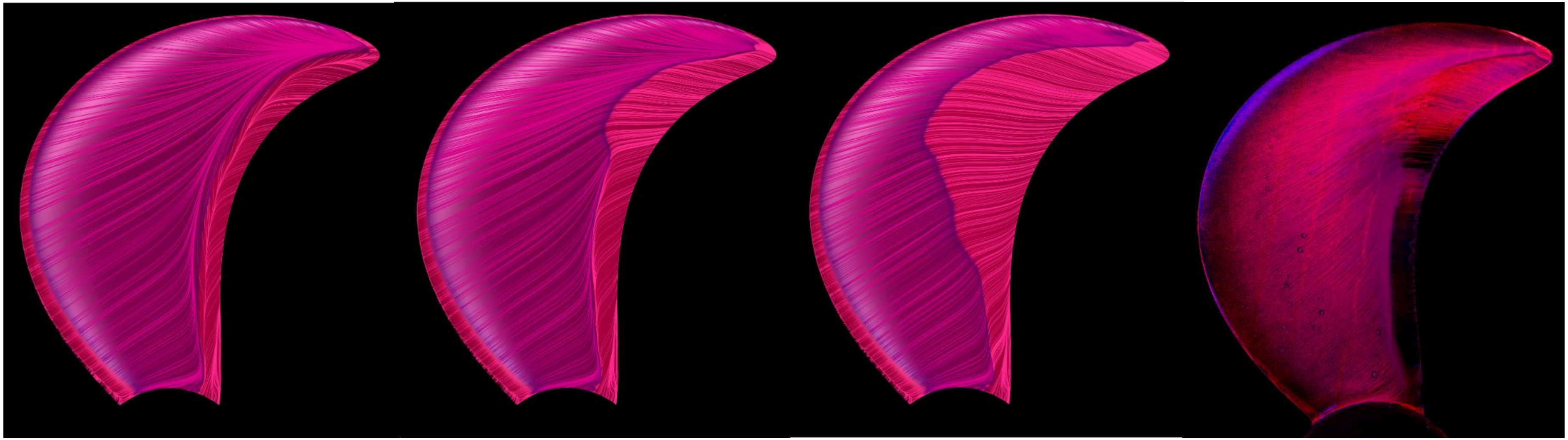
- CFD including transition LCTM (Local Correlation Transport Model) modelling to solve transition and flow separation

- LCTM models exhibit high sensitivity due to their reliance on local turbulence quantities
  - boundary conditions
  - turbulence decay control



Influence boundary conditions / turbulence decay control



Tu = 1.0% | Tu = 1.35% | Tu = 2.0% | EXP

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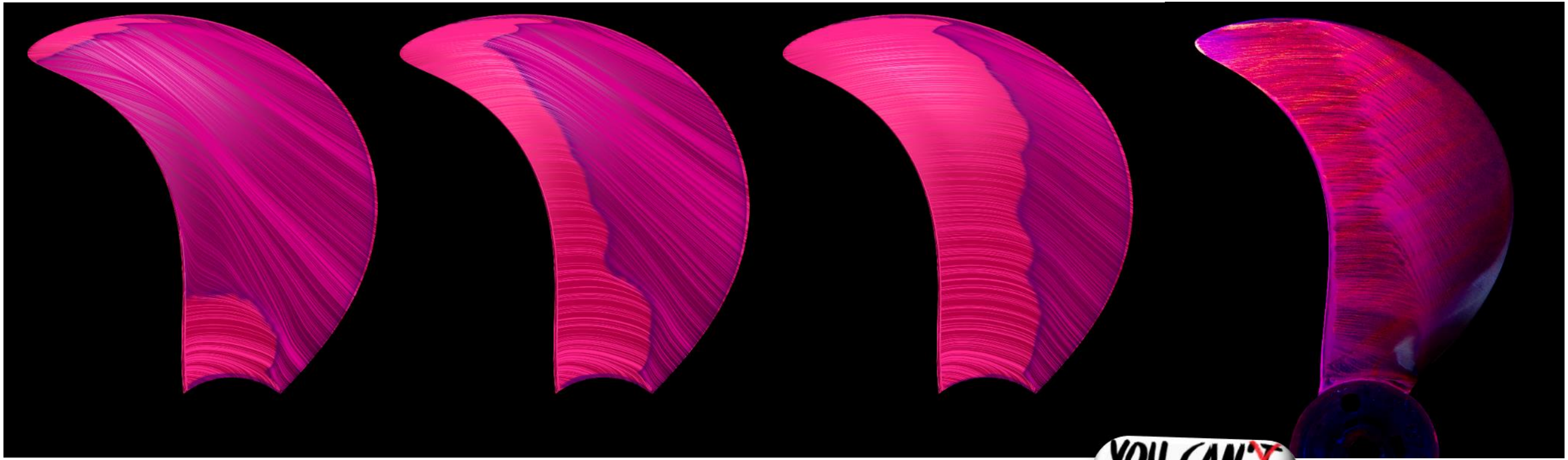

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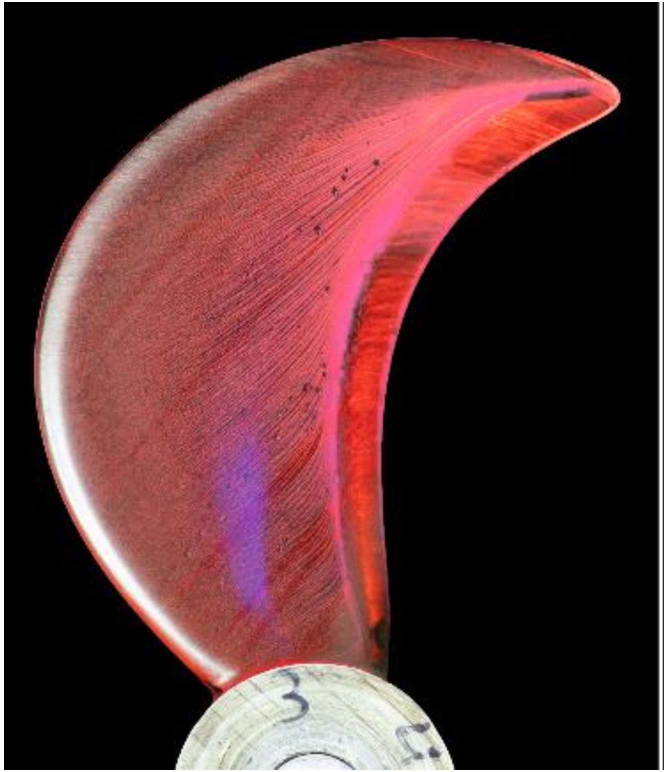
Extrapolation challenges

- Extrapolation of model-scale results towards full-scale predictions are challenging if the flow behaviour at model-scale is not known

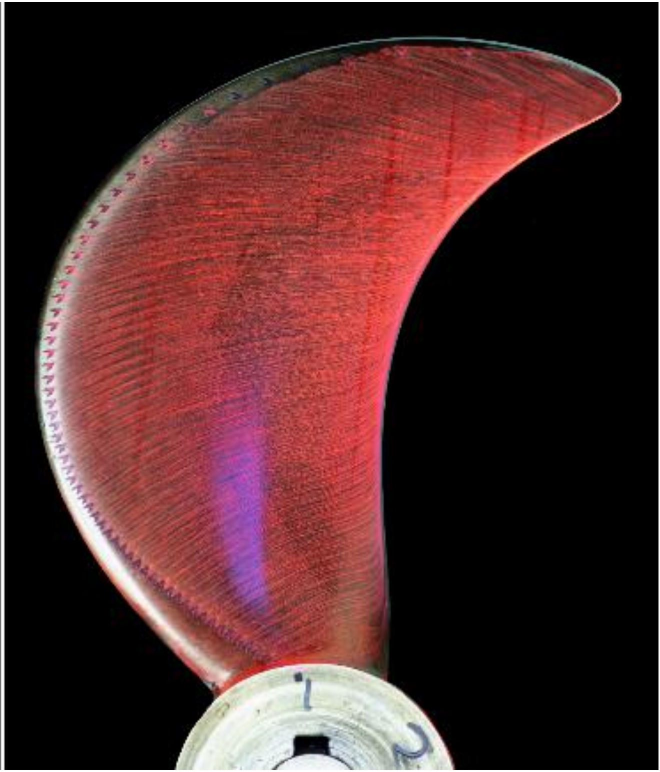
- Thus, a more effective approach would involve striving for boundary layer control and achieving flow similarity. This means a turbulent boundary layer at model-scale

Model-scale solution

- Boundary layer control towards flow similarity
- Applying turbulators to efficiently trip the laminar boundary



No BL control



Turbulators

Model-scale solution

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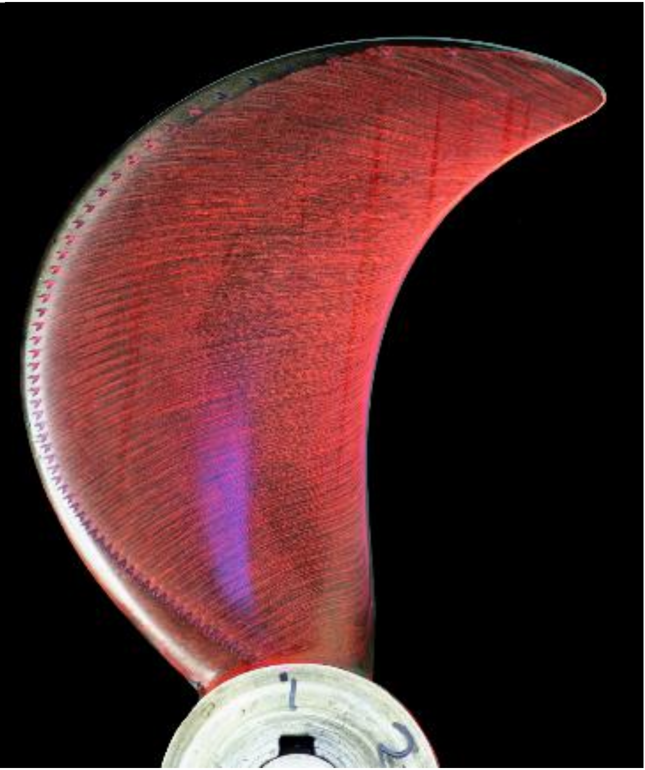
High Reynolds number

CFD



Experiment

Model-scale solution

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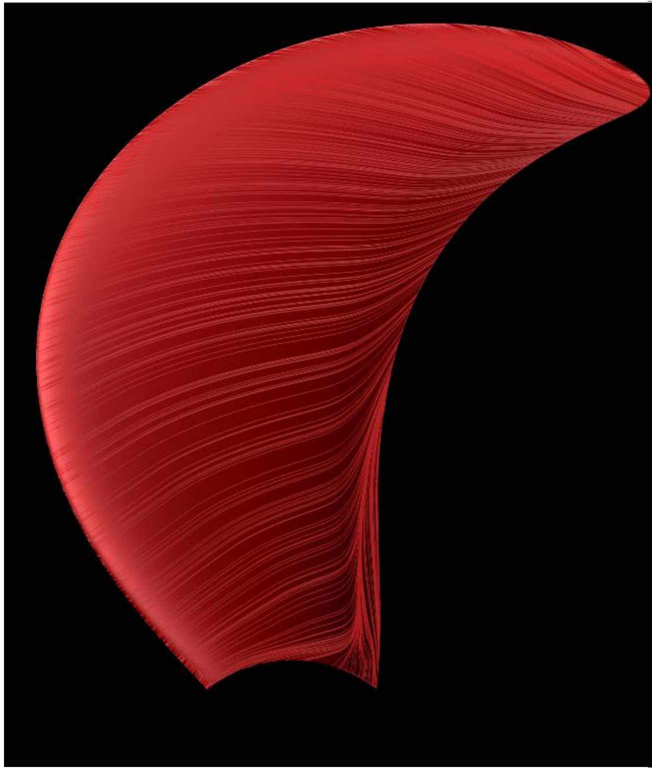
Low Reynolds number



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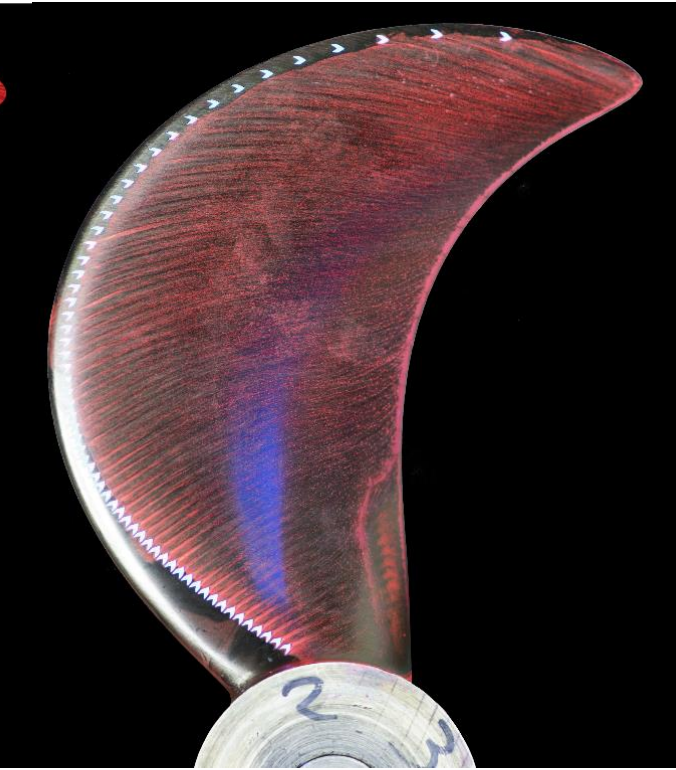
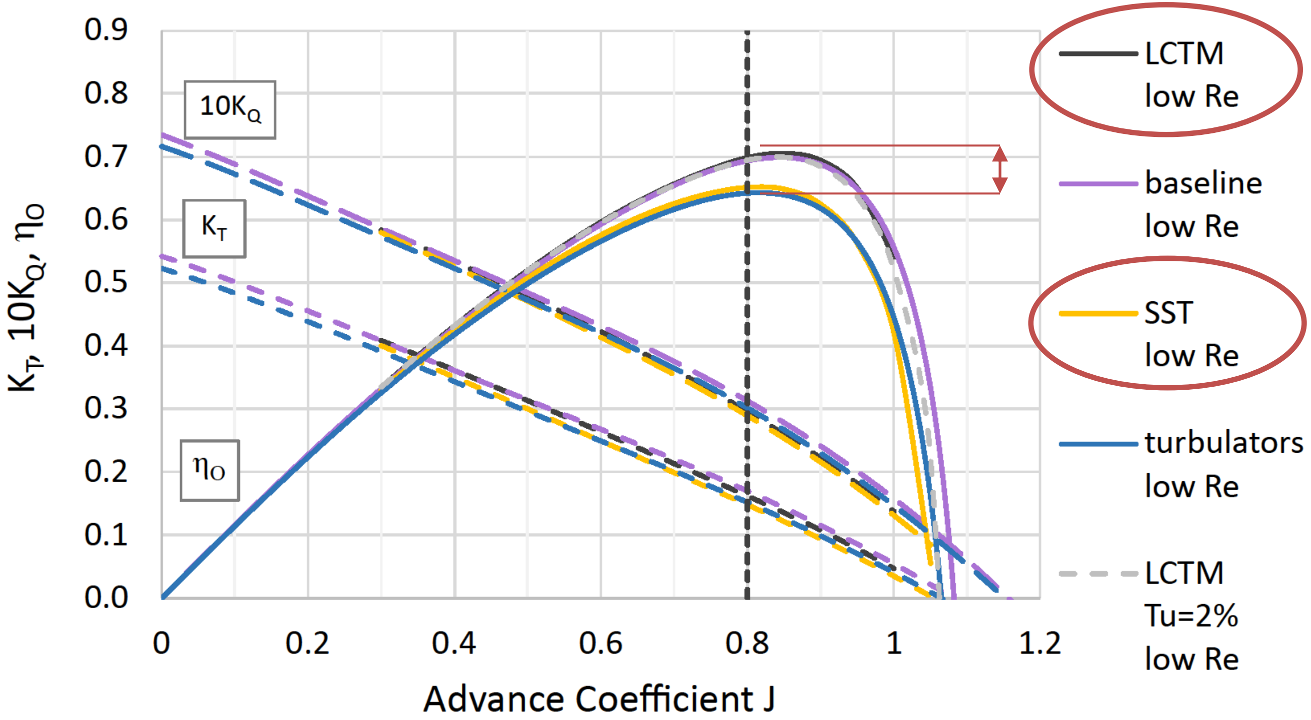


Experiment

Open water characteristics

Untripped vs tripped

- Absolute difference $\Delta\eta_o$ of about 5% at the design condition
- Thrust coefficient K_T differs with values from 6% to 10%



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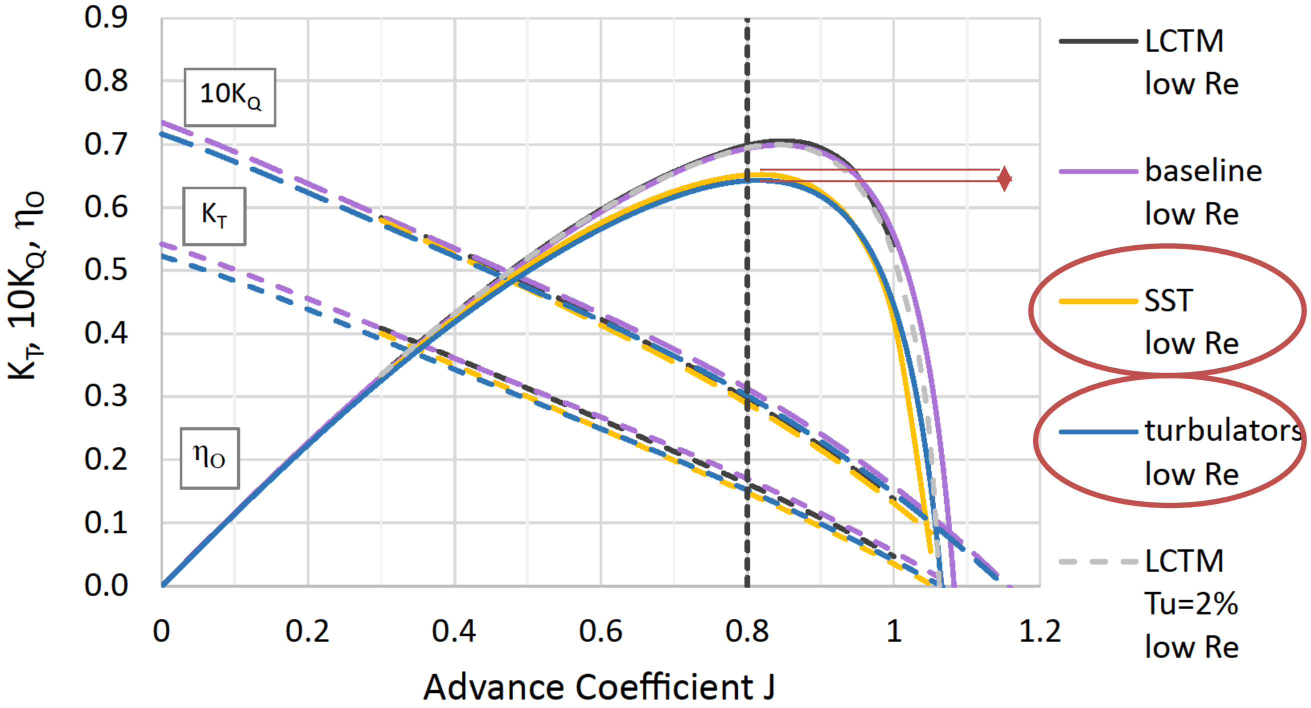
Tripped/turbulent CFD simulations

- $\Delta\eta_o$ < 1% over the complete J range
- Difference for K_T and K_Q < 2-3%
- Negative effect (parasitic drag) turbulators is negligible



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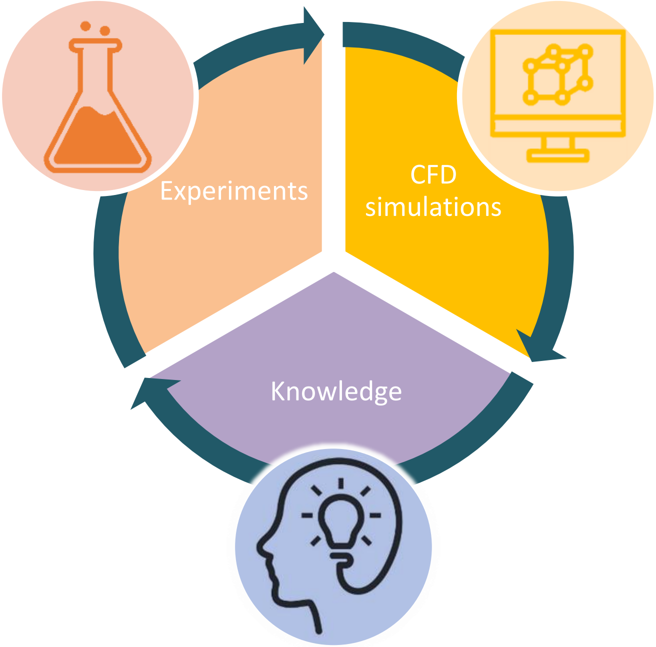
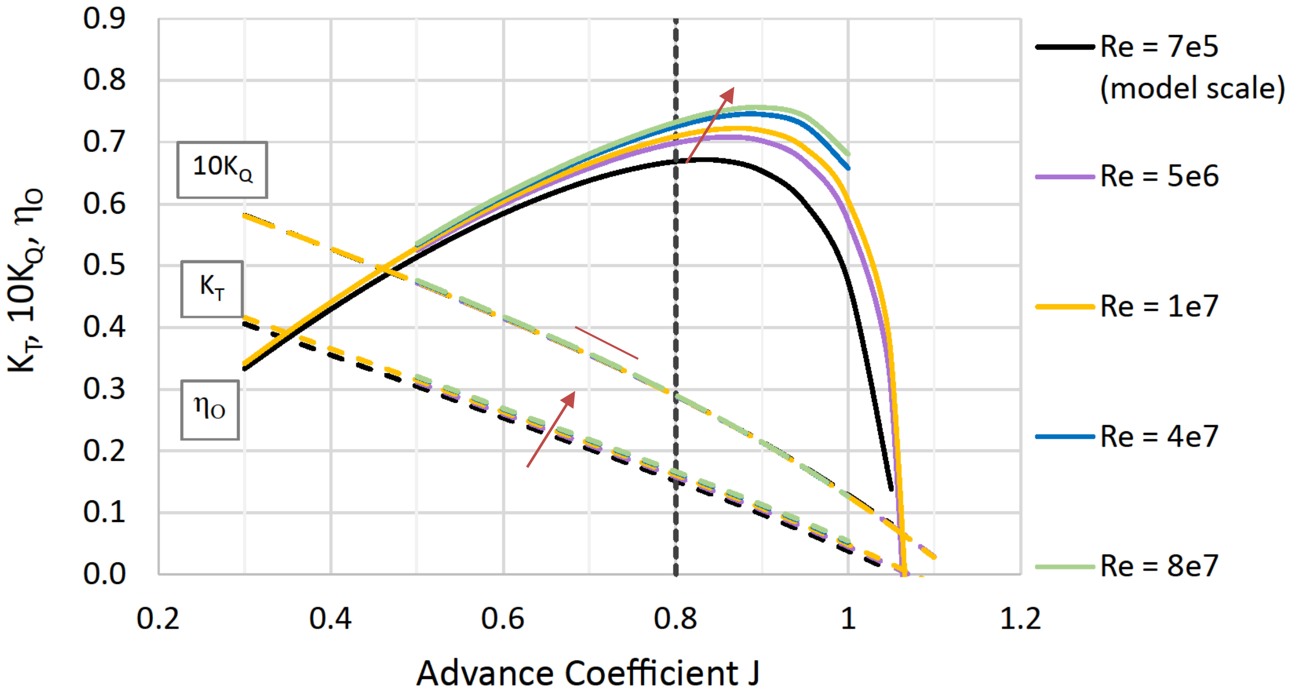


Full scale CFD

- Reynolds scaling primarily affects the thrust coefficient
- Torque coefficient experience minimal change
- Overall increase in open-water efficiency



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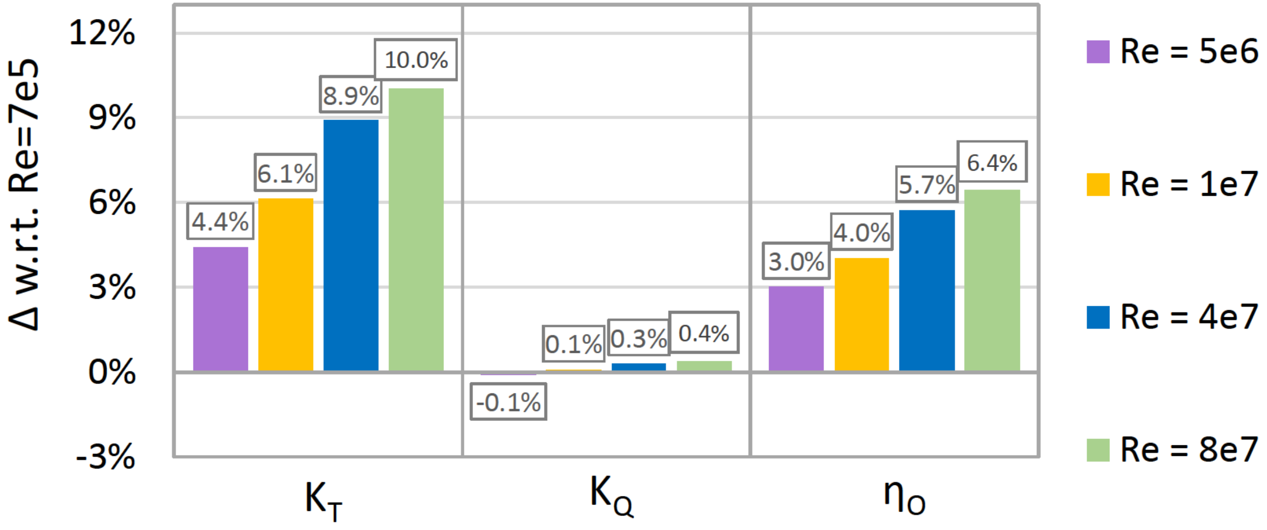


Full scale extrapolation

- Most extrapolation procedures only correct for a difference in drag
- But a turbulent boundary layer at the same Reynolds number significantly impacts lift

- 1978 ITTC Performance Prediction Method

$$K_{T_s} = K_{T_m} - \Delta K_T,$$

$$K_{Q_s} = K_{Q_m} - \Delta K_Q,$$

$$\Delta K_T = -0.3\Delta C_D \left(\frac{P}{D}\right)\left(\frac{cZ}{D}\right),$$

$$\Delta K_Q = 0.25\Delta C_D \left(\frac{cZ}{D}\right),$$

$$\Delta C_D = C_{D_m} - C_{D_s},$$

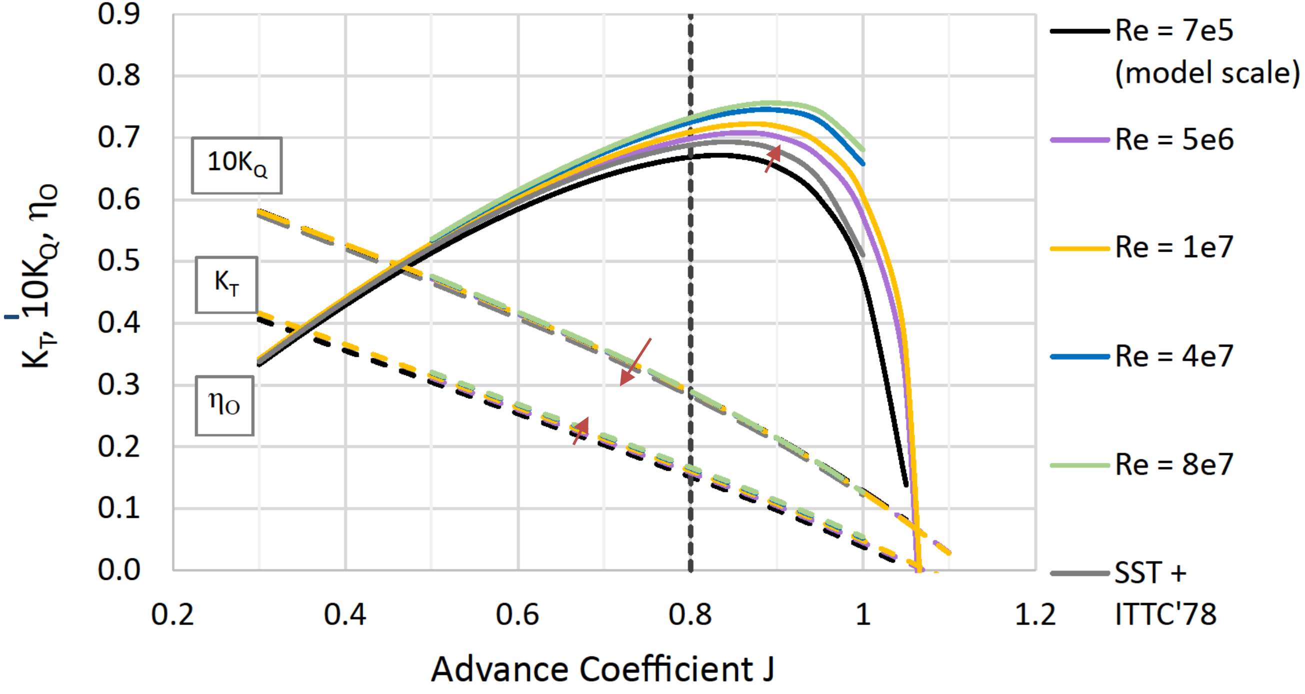
$$C_{D_m} = 2\left(1 + 2\frac{t}{c}\right)\left[\underbrace{\frac{0.044}{(\mathrm{Re}_m)^{1/6}}}_{\text{turbulent}} - \underbrace{\frac{A}{(\mathrm{Re}_m)^{2/3}}}_{\text{laminar}}\right],$$

$$C_{D_s} = 2\left(1 + 2\frac{t}{c}\right)\left[1.89 + 1.62\log_{10}\left(\frac{c}{k_p}\right)\right]^{-2.5}.$$

Hoerner. Fluid-Dynamic Drag. Theoretical, Experimental and Statistical Information, 1965

Full scale extrapolation

- Wrong trends observed by applying the ITTC’78 extrapolation method for model-scale results



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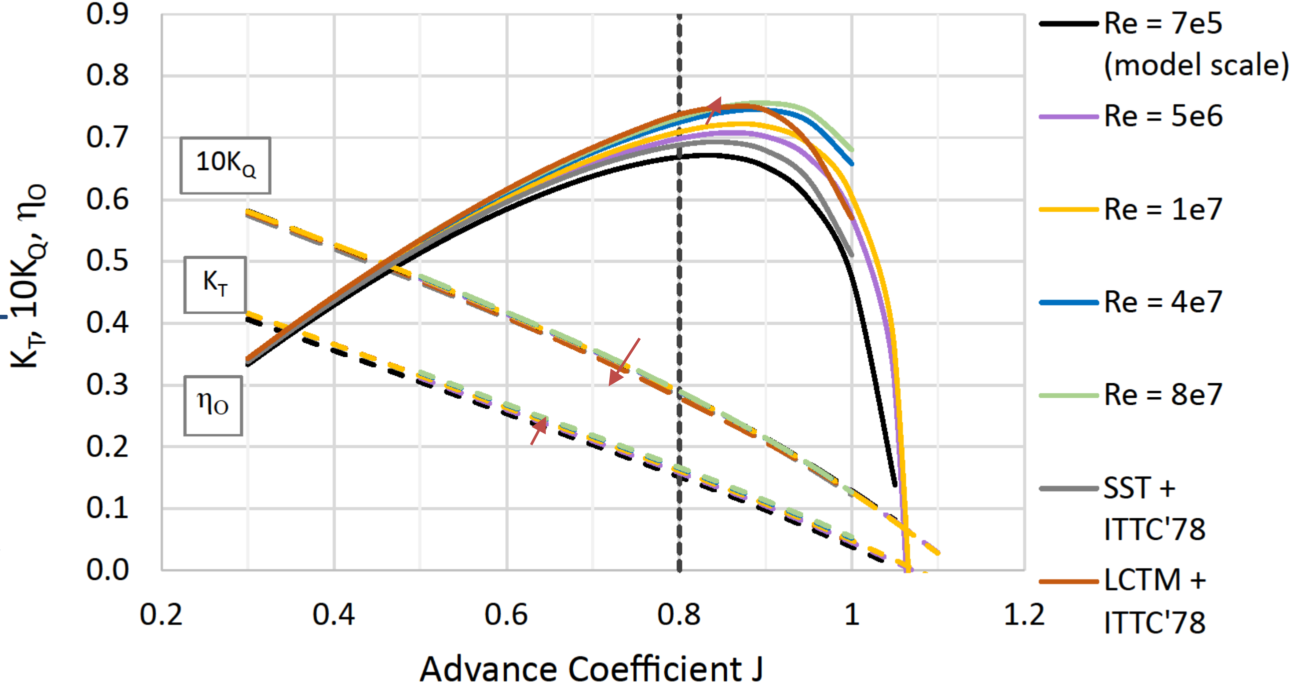

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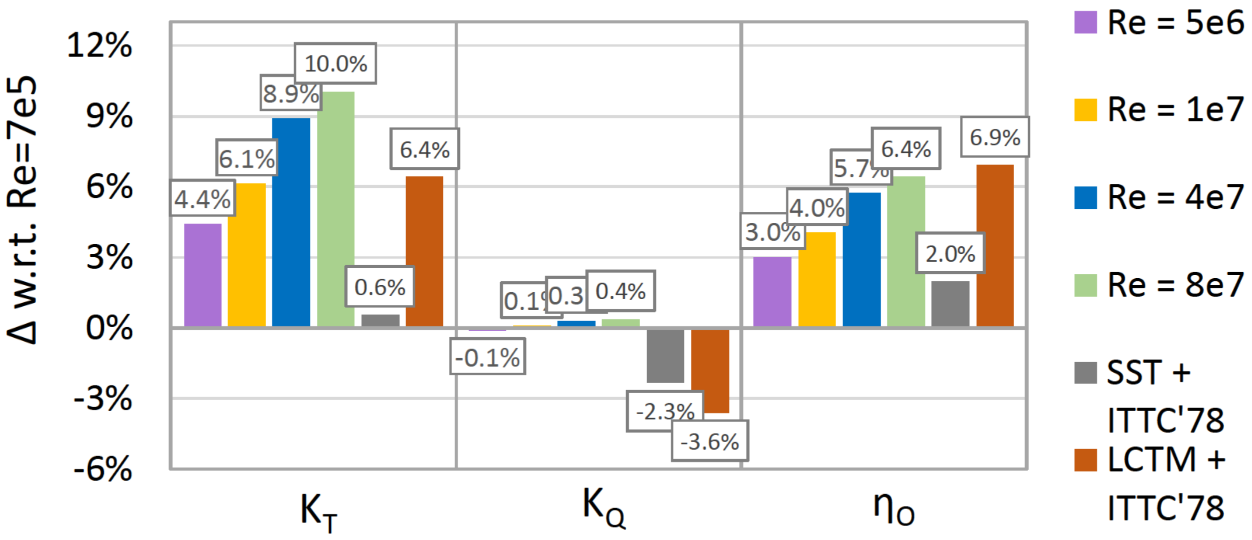

Conclusions and outlook

- It is possible to accurately predict the performance of an open-water propeller at model-scale, including the effect of transition and flow separation, using transition modelling
- However, small discrepancies between experiments and simulations can only be achieved if the onset of transition and possible flow separation is known a priori

- Therefore, a feasible alternative is demonstrated, since the CFD results performed with a turbulence model provide a very good comparison with the open-water experiments including turbulators at the leading edge (flow similarity)
- A turbulent boundary layer during model-scale experiments offers a review of current extrapolation methods towards a CFD-based extrapolation procedure

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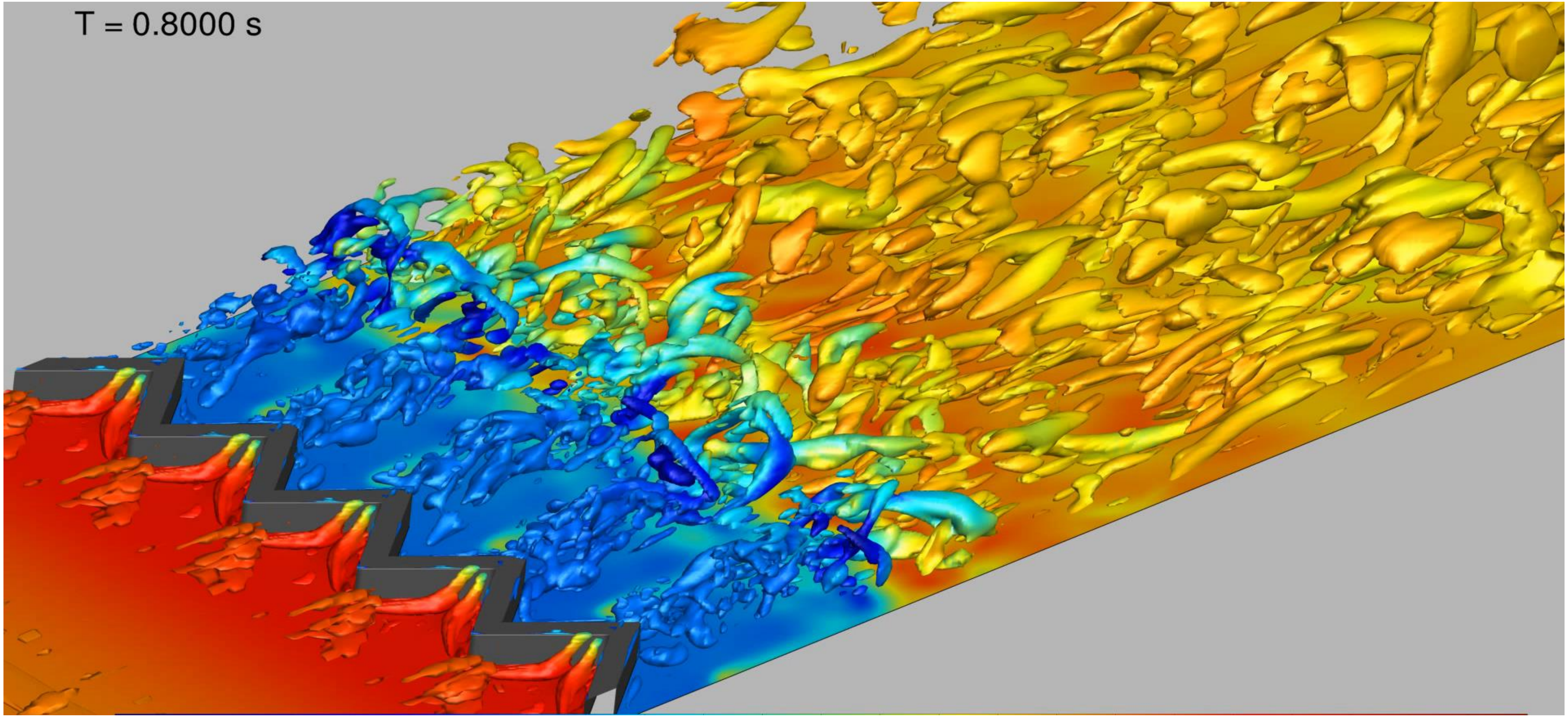
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