A MARINE TURBOCHARGER RETROFITTING PLATFORM

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Turbocharger Retrofitting Platform

A turbocharger retrofitting platform, utilizing 1D models for calculating turbomachinery components maps and a fully coupled process for integration with the turbomachinery components and the diesel engine, has been developed. The platform comprises two modes of operation, allowing the retrofitting process to be fully automatic.

- **Available turbo-components examination to select the one that best matches the entire engine system, aiming to retain or improve the diesel engine efficiency**
- **Centrifugal Compressor re-design to match the entire system in an optimum way**

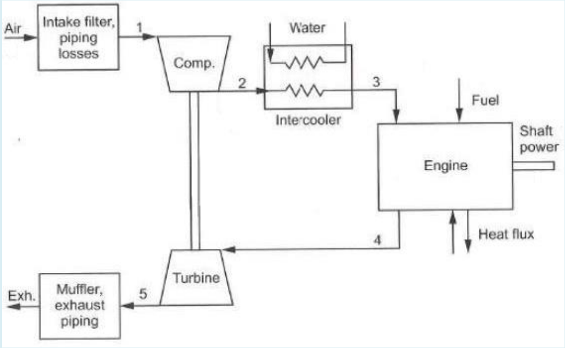
Contents

Methodology

Contents

Turbocharged Diesel Engine Simulation Framework

- Single zone thermodynamic combustion model for the closed diesel engine cycle.
- 1D centrifugal compressor model based on methodology presented by Galvas [(1)].
- 1D radial turbine model based on methodology presented by Wasserbauer [(2)] .



(1) Galvas, M.R., "Fortran program For predicting off design performance of Centrifugal Compressor." Technical Report No. TN D-7487. NASA Lewis Research Center, Cleveland, Ohio. 1973.
(2) Wasserbauer, C.A. and Glassman, A. J., “Fortran Program for predicting off-design performance of Radial-Inflow Turbines.” Technical Report No. TN D-8063. NASA Lewis Research Center, Cleveland, Ohio. 1975.

Turbocharged Diesel Engine Simulation Framework

- **Validation of the model of each individual component has been extensively described in another publication[1] .**
- **Diesel Engine model is capable of being calibrated based on data available from shop trials.**
- **T/C Diesel Engine matching criteria checking:**
  - ✓ T/C must provide the necessary boost pressure, in order for the Diesel Engine to generate the demanded nominal power.
  - ✓ The turbo-components operating nominal points should be in high efficiency area.
  - ✓ Compressor operating line distance from surge line must be as large as possible.

(1) Ntonas, K. ,Aretakis, N. , Roumeliotis, I., Pariotis, E., Paraskevopoulos, Y. and Zannis T. , "Integrated Simulation Framework for Assessing Turbocharger Fault Effects on Diesel Engine Performance and Operability." ASCE Journal of Energy Engineering (2020)

Turbocharger retrofit using available turbo-components (Mode 1)

The platform first mode provides an automatic T/C retrofit choice by examining all turbo-components (compressors and turbines) available in data base.

- **The data-base has been developed with 13 different turbocharger 1D geometries.**
- **It sorts the available turbo-components, the technical specifications of which are stored in a database, according to the matching quality and the calculated overall performance.**
- **It is capable of checking specific turbo-components as retrofitting parts, leading to a high computational cost reduction, if specific original turbocharger component (e.g. turbine) is available.**
- **The platform integrates a flow trimming tool.**

Centrifugal Compressor Redesign (Mode 2)

In the second mode, an optimization procedure is followed, redesigning the compressor in order to match the entire system in an optimum way, retaining the original turbine.

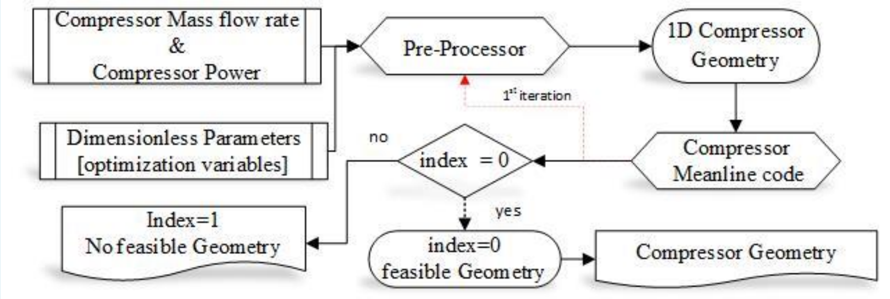
- **Usage of dimensionless parameters for a optimization process, fully automatic**
- **Constant variables ranges are imposed**
- **Random initial geometry**
- **A Multi-Objective Particle Swarm and a Downhill Simplex techniques are sequentially coupled.**
- **Limited to vaneless diffuser centrifugal compressor**

Parameter	Range	Parameter	Range
Z	(6,40)	R_{1H}/R_{1T}	(0.25,0.70)
N_S	(0.45,1.25)	MN_3	<0.95
Φ_2	(0.1,0.5)	β_2	(0,80)
R_{1T}/R_2	(0.3,0.8)		

$\eta_{comp,AD}$	PR	MN_{1t}	$\dot{m}_{cor}$	N_{comp}
(0,0.94)	>1	<1.05	$(\dot{m}_{surge}, \dot{m}_{choke})$	$= N_{turb}$

Centrifugal Compressor Redesign (Mode 2)

The usage of dimensionless parameters is achieved by coupling a typical compressor 1D mean line model with a pre-processor, capable of transforming dimensionless parameters into 1D geometry.

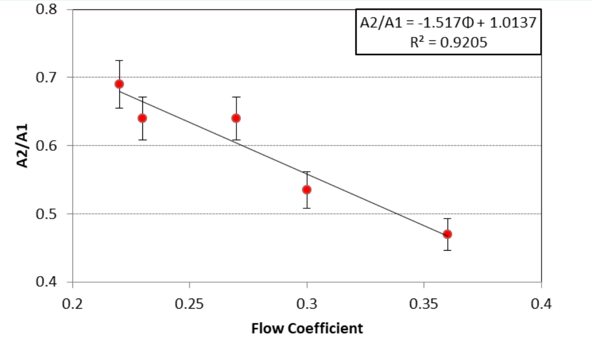


- **Input data: Pwrturb, $\dot{m}$, Z, NS, Φ2, R1T/R2, R1H/R1T, MN3, β2**
- **Output data: R1h, R1t, R2, R3, b2, b3, Z, β1m, β2**
- **The compressor model integrates constraints that ensure physically acceptable solutions, while it reduces computational cost.**
- **Power and mass flow can be found in shop trials data.**

Centrifugal Compressor Redesign (Mode 2)

Modification of the single-zone model

- **The single zone model is unable to calculate the impact of impeller outlet blade length in recirculation and active flow region generation.**

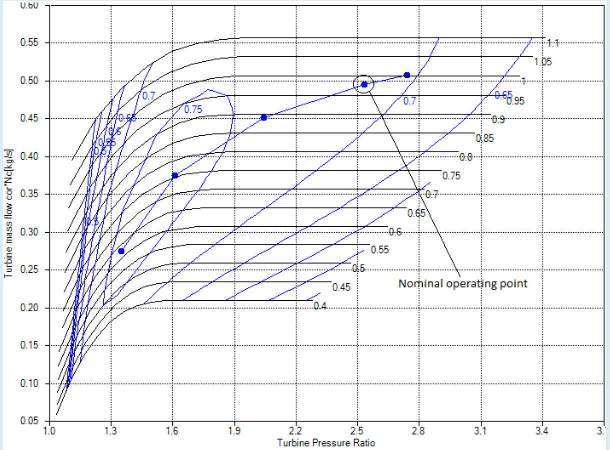


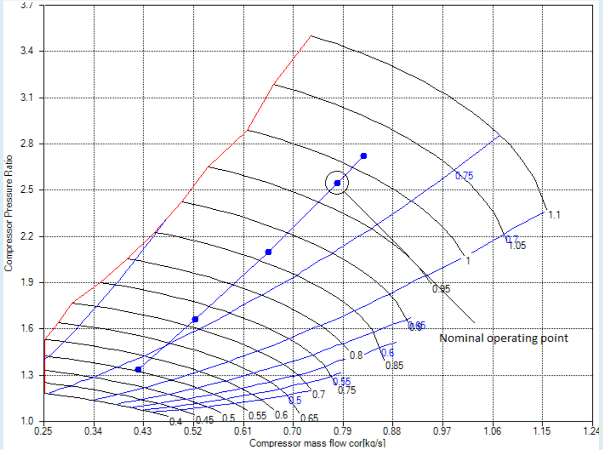
- **An additional impeller outlet blade length restriction is added to overcome the single zone problem.**
- **The restriction is developed based on a number of compressor measured geometries.**

Contents

Test Case

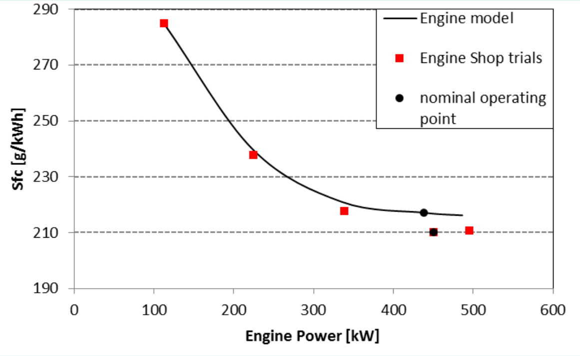
- A T/C 5-cylinder 4-stroke diesel generator is to be retrofitted
- Diesel Engine model is calibrated
- Shop trials are available





Test Case

- The specific fuel consumption against engine power for five different operating points (Load: 25, 50, 75, 100 and 110%).



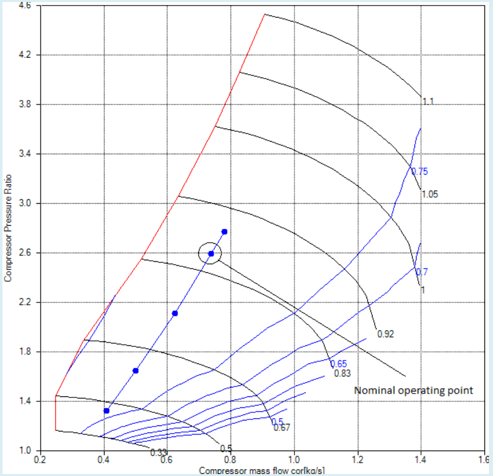
- Maximum SFC deviation: 2.6%

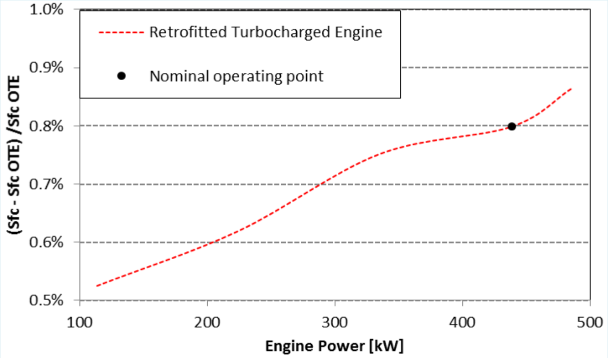
- Retrofit Options:

1. Compressor retrofit, using available compressors.
2. Entire turbocharger retrofit, using available compressor and turbine pairs.
3. New turbocharger compressor design (compressor optimization).

Option 1: Compressor retrofit

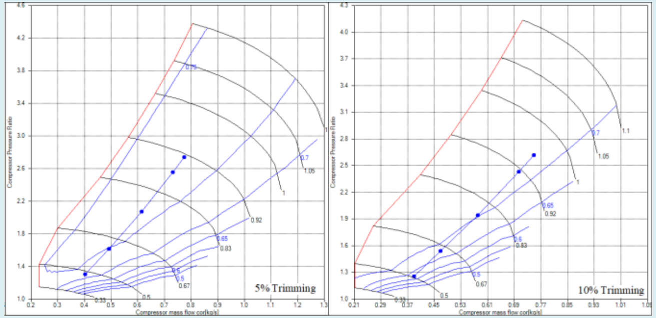
- Original Turbine is retained.
- Low cost process.
- Compressor is chosen from the inventory of available compressors.
- 12% maximum T/C speed drop.
- 0.8% increase in SFC at nominal operating point.
- The platform makes the best choice among those in database, but even the most suitable one is not perfectly fitted for the given diesel engine.

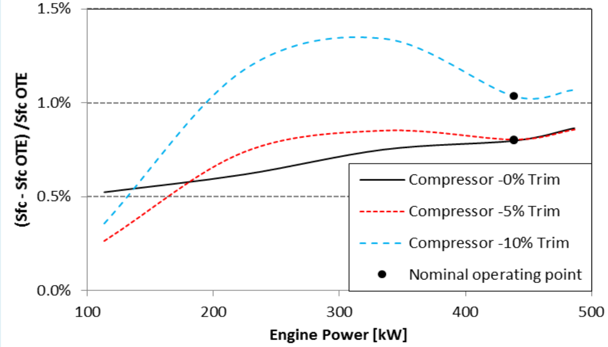




Option 1: Compressor retrofit: manual flow trimming

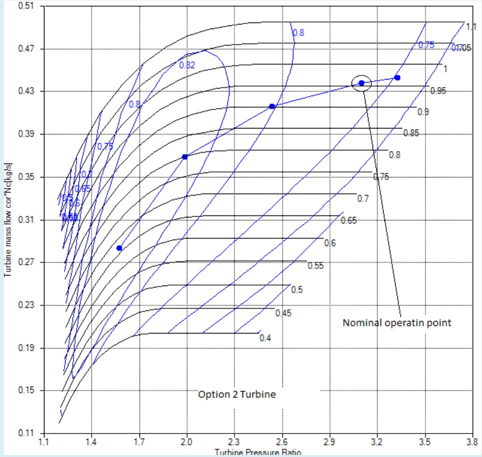
- Compressor blades are cut, moving the surge line away from the operating line.
- For the sake of demonstration.
- 5% and 10% compressor trimming.
- Both trimmed compressors operation is stable.
- Both compressors are not working in over-speed conditions
- 5% trimmed compressor is considered more appropriate for this case.

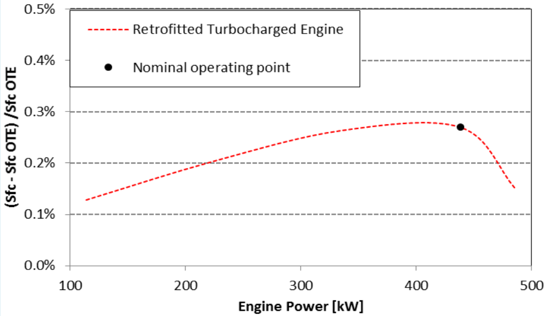




Option 2: Entire turbocharger retrofit

- The entire turbocharger is retrofitted.
- Both turbo-components are chosen from the inventory of available compressor and turbine pairs.
- Low cost process.
- Higher cost process than option 1.
- Platform chooses the same Compressor with option 1
- 11.37% speed increases due to the turbine replacement
- 0.27% SFC increase at nominal point
- Lower SFC in comparison to option 1
- Need for data-base to include more turbo-components.

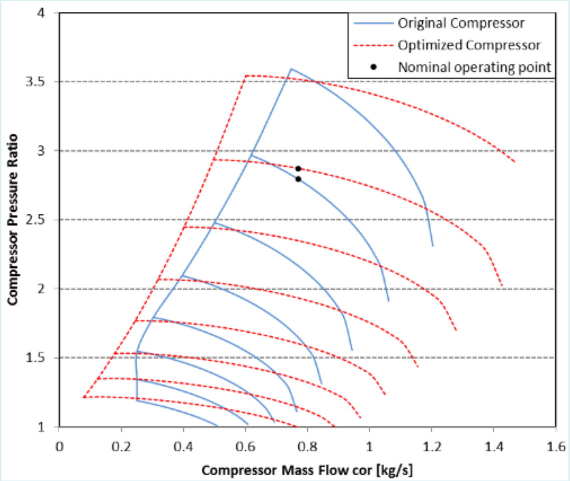




Option 3: New compressor design

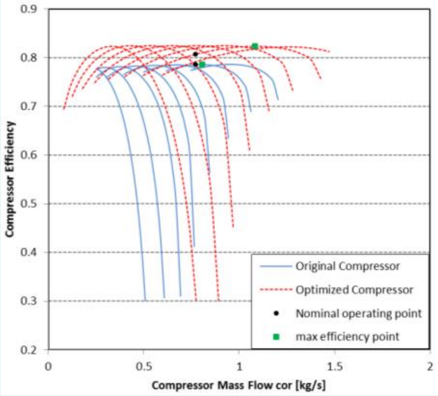
- **New compressor redesign using the optimization mode.**
- **High cost process.**
  - The cost for a high capacity marine centrifugal compressor manufacturing may exceed the value of 10000$
- **Both mass flow and turbine power are available from shop trials.**
- **Extra restriction: impeller hub radius.**
  - Ensures that impeller can fit to specific diameter turbocharger axis.
- **Compressor geometry has similar size to the original one.**
- **12.39% pressure ratio increase at nominal operating point.**

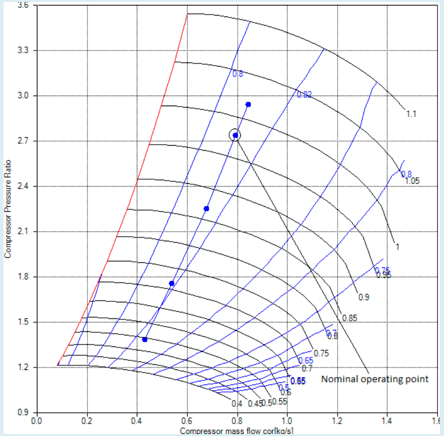
R_{1H}/R_T	R_{1T}/R_2	A_2/A_1	Φ	β_{1M}	β_2
4%	10%	6%	12%	71%	37.8%

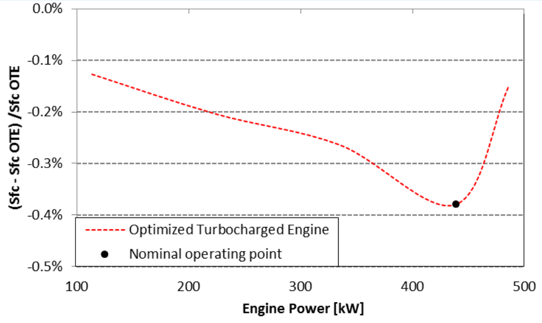


Option 3: New compressor design

- **3.8% maximum efficiency increase.**
  - 34.6% design point movement.
- **2% Efficiency increase at nominal operating point.**
- **Optimized compressor operates with a sufficient distance from the surge line.**
- **0.38% reduction in nominal T/C speed.**
- **0.27% SFC decrease at nominal operating point.**



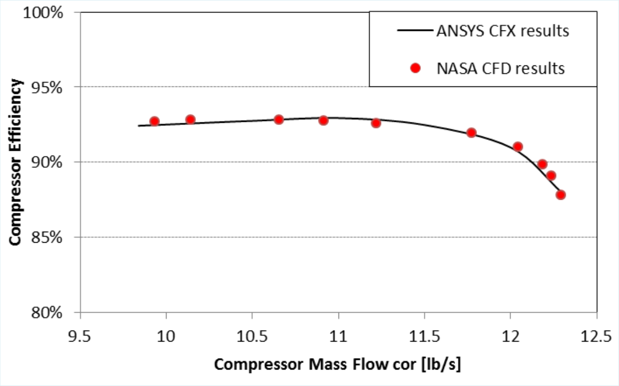




Platform mode 2 CFD Validation

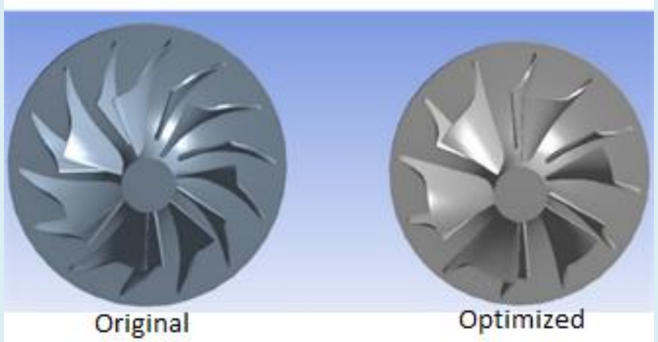
A CFD analysis has been carried out, as a mean of validating the compressor optimization tool capability to capture the performance trends based on geometry variation by comparing the pressure ratio and efficiency between CFD and corresponding 1D method.

- **Steady-RANS simulation conducted in ANSYS CFX 17.0.**
- **Single passage simulation.**
- **2 millions impeller mesh size and 140000 diffuser mesh size.**
  - Maximum y+ lower than 2.58.
- **NASA B30-D2 vaneless diffuser centrifugal compressor is used as validation case.**
  - 0.5% maximum error for the efficiency curve at nominal speed.

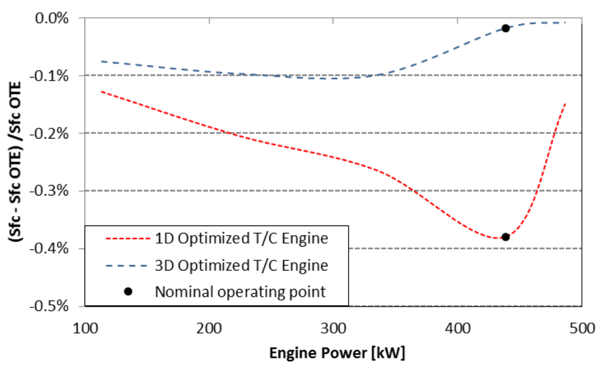


Platform mode 2 CFD Validation

- A new transformation from 1D to 3D geometry technique is developed
- CFD simulation at nominal operating point is performed
- The 1D model is able to capture the performance trend based on geometry variation
  - 0.8% efficiency difference between 1D and CFD model.
  - 2.52% pressure ratio difference (expected due to single zone model nature)
- 0.02% decrease in SFC for the nominal operating point.



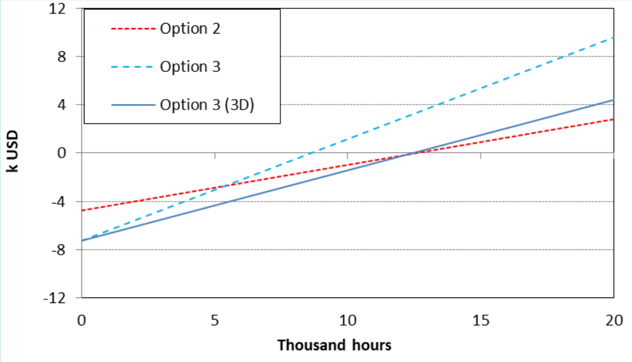
Parameter	1D model	CFD
Total Pressure Ratio	+12.39%	+14.91%
Compressor Efficiency	+2.1%	+1.3%



Retrofit cost analysis (all three options, including 3D analysis)

Indicative costs are used:

- Centrifugal compressor (one part order) cost.
- T/C purchase cost.
- Impeller CNC milling cost.
- Scroll housing casting cost.
- Fuel cost (typical at the period of writing this paper).



Payback period calculation

- Option 1 has the lower investment cost.
- The payback period is calculated based on option 1.
- Option 2: 12574h
- Option 3 (1D): : 8621h
- Option 3 (3D) : 12441h

Option 3 seems to be the best choice (even with this reduction), having the shortest payback time.

Automatic retrofitting platform achievement

- Retrofit process relying on engineers' personal judgment may not be optimal and thus a turbocharged marine diesel engine unnecessary efficiency degradation occurs.

  - **Fuel consumption increase = NOx & CO2 increase.**
  - **Climate change and Global warning recrudescence.**
  - **Higher operation cost.**

- The mass usage of the retrofitting platform, it is expected that the retrofit process, will provide the best retrofit solution, leading to:

  - **Lower Diesel operation cost.**
  - **Fuel consumption decrease= NOx & CO2 decrease.**
  - **Climate change and Global warning prevention.**
  - **Productivity of turbocharger manufacturers increases = time spend decrease**

Contents

Summary & Conclusions

- A marine turbocharger retrofitting platform, presented in this work, utilizes 1D models for calculating the turbomachinery components maps and a fully coupled process integrating the turbomachinery components and the diesel engine. Having two modes of operation, it allows the T/C retrofitting process to become fully automatic.

- In the first mode, all available turbo-components (compressors and turbines) are examined in order to select the one that matches the entire engine system, while retaining or improving the diesel engine efficiency.

- In the second mode, an optimization procedure is followed, in order to redesign the compressor to match the entire system in an optimum way.

- The platform is applied to a real retrofitting case study where three retrofitting options are analyzed

  - **In option 1 and 2 (1st mode) the initial performance cannot be restored using particular off-the-self solutions, having a specific fuel consumption increase about 0.8% for option one and 0.27% for option two in nominal operating point.**

  - **In option 3 (2nd mode) the entire diesel engine system efficiency improvement is reached, leading to a SFC decrease about 0.27%.**

  - **CFD analysis: 0.8% increase in efficiency trend and a 2.52% in pressure ratio trend.**

    - 1D model is a reliable tool during 1D design.

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Thank you very much for your attention