EFFICIENT SYSTEMS AND PROPULSION FOR SMALL AIRCRAFT

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Aeronautics and Air Transport

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Engine simulation models for the cycles of BE1 and report on obtained performance data

Model development with the Gas turbine Simulation Program (GSP)

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SEVENTH FRAMEWORK PROGRAMME

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Abstract

This report describes the work conducted by TUD for WP 1.3.3 of the ESPOSA project for the development of the BE1 engine simulation model in NLR's Gas turbine Simulation Program, GSP. Results include simulation results, validation and the GSP model project files. The model is based on simulated data from PBS Velká Bíteš, Czech Republic, (PBS). The model is provided separately in digital format with the file Eposa_D1331_BE1_rev2.0.mxl. A number of application cases is demonstrated for engine and control system development.

The GSP model is sufficiently accurate to perform trade-off (effect/sensitivity) studies for the engine development program. For simulations that require high accuracy, the actual component maps should be implemented in the GSP models in place of the generic ones currently used. This relatively simple task can be performed by the model end user (engine OEM) after which absolute performance prediction accuracy will be higher making the model suitable for control system design, including stall margin assessments, system identification, control schedule evaluation/optimization and other analysis work.

Summary

This report describes the development of a performance model for the Esposa project BE1 turboprop engine design of PBS Velká Bíteš, Czech Republic. The PBS name for the engine is TP-100. The turboshaft version is named TS-100. The engine has a nominal power output of about 200 kW. The model has been developed using the GSP Gas turbine Simulation Program (see ref. [1] and www.gspteam.com), a component based gas turbine system modeling environment. GSP's flexible object-oriented architecture allows steady state and transient simulation of virtually any gas turbine configuration using a user-friendly drag & drop interface. Gas turbine engines can quickly be modeled in this modeling environment to perform various analyses.

The GSP model has been prepared using the following performance data[1]:

- TP100 performance data as generated by performance deck (ref. [2])
- A limited number of off-design operating point data sheets from PBS performance deck
- Scaled compressor and turbine maps from other sources:
    - for the compressor, the actual component map[2] was used, see ref. [8],
    - for the gas generator turbine the standard generic GSP map was scaled,
    - for the power turbine the map of the similar (but larger) Esposa BE2 engine was scaled, see ref. [3].

The model has been tuned to these data resulting in a maximum 2% deviation from design point and maximum 5% deviation from off-design performance data. Percentages are relative to design point parameter values. This is well within range for sensitivity and effect study analysis and a demonstration of gas path analysis GPA (Esposa WP 4.2).

A conflict seems to emerge at the combustor energy balance: a match with PBS design performance data could only be obtained with a combustor efficiency of 94%. This is unusually low and therefore the origin of this conflict must be resolved.

[1] Note that a full performance deck and the real component maps are still being refined by PBS.

[2] Measured on the reference test engine core, then treated (smoothed) according to the standards set out by PBS to create the compressor characteristic.

After reconfiguring the models with the actual component maps at PBS, a more accurate match can be obtained.

The model has been demonstrated for the following application areas:

- design point analysis and optimization
- off-design performance analysis
- transient fuel step response analysis for system identification
- transient schedule generation using limiters for turbine entry temperature and stall margin

The model is further to be used to demonstrate gas path analysis concepts for condition monitoring in Esposa WP4.2.

The GSP model is sufficiently accurate to perform trade-off (effect/sensitivity) studies for the engine development program. For simulations that require high accuracy, the real maps should be implemented in the GSP models. This relatively simple task can be performed by the model end user (engine OEM) after which absolute performance prediction accuracy will be higher, making model suitable for control system design, including stall margin assessments, system identification, control schedule evaluation/optimization and other analysis work.

The model is provided separately in digital format with the file Eposa_D1331_BE1_rev2.0.mxl.

Table of Contents

Acronyms

Abbreviation	*Description*
BE1 (BE2)	Engine type designation; Basic Engine 1 (2)
c	Flow velocity [m/s]
DP	Design point
GPA	Gas Path Analysis
GSP	Gas turbine Simulation Program
H	Flight altitude [m]
HP	High Pressure
Hv	Fuel lower heating value [MJ/kg]
ISA	International Standard Atmosphere
ITT	Inter turbine temperature ºC (= Tt4)
N, N%	Rotor speed, % rotor speed
NASA	National Aeronautics and Space Administration
CIAM	Central Institute of Aviation Motors
OD	Off-design
P, Pt	Pressure, Total pressure
PBS	PBS Velká Bíteš, Czech Republic
PR	Pressure Ratio
PW	Power [kW]
RR	Ram Recovery
SFC	Specific fuel consumption
SL	Sea Level
T, Tt	Temperature, Total temperature
V	Air speed [km/h]
W	Mass flow [kg/s[
Wc	Corrected mass flow (W*sqrt(theta)/delta) [kg/s]
WF	Fuel flow
WP	Work Package
η (ic, itgg, itpt)	Efficiency (isentropic compressor, gg turbine, power turbine)
U/Cs	Velocity Ratio

Indices

Abbreviation	*Description*
b	Burner or combustor
c	Compressor
gg	Gas generator
pt	Power turbine
tgg	Gas generator or HP turbine
c	Corrected
I	isentropic
t	Turbine

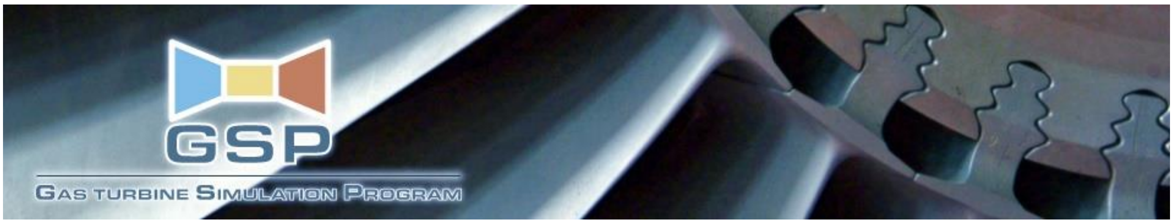
1 Introduction

The present report is a deliverable for the SP1/WP1.3 subproject of the ESPOSA project rewarded in the fourth call of the 7th Framework Program of the EU. This report describes the development of the BE1 engine performance model using the Gas turbine Simulation Program GSP.

The Gas turbine Simulation Program, GSP [1] is a 0-D component based modeling environment developed by Dutch National Aerospace Laboratory NLR and Delft University of Technology. GSP's flexible object-oriented architecture allows steady state and transient simulation of virtually any gas turbine configuration using a user-friendly drag & drop interface. Gas turbine engines models can be rapidly prepared in order to perform various analyses. These include performance prediction, control system performance analysis/optimization, diagnostics/prognostics, failure analysis, structural and thermal load prediction and life prediction.

2 The Gas turbine Simulation Program GSP

This gas turbine simulation tool is capable of calculating both steady-state and transient gas turbine performance for various operating conditions using a user-friendly drag-and-drop interface with on-line help running under Microsoft Windows. Besides being a performance prediction tool, GSP is especially suitable for parameter sensitivity analysis such as: ambient (flight) condition effects analysis, preliminary design analysis, installation (loss) effects analysis, analysis of effects of certain engine malfunctioning (including control system malfunctioning), component deterioration effects analysis, emissions and jet noise.



GSP is primarily based on 0-D modeling of the thermodynamic gas turbine cycle. This implies that the flow properties are averaged over the flow cross section areas at the interface surfaces of the component models (inlet and the exit). Component model stacking is used to create the thermodynamic cycle of the engine of interest. The exit gas condition of a component forms the inlet gas condition of the next component in the configuration. The gas model is based on NASA’s CEA program ([4], [5]) to calculate the thermodynamic properties based on the chemical composition.

GSP uses a main window (see Figure 1) which contains the various model components which are conveniently grouped in specific component libraries identified by the text on the tab of every library sheet. These components can be dragged into the model window of the project to arrange the engine cycle.

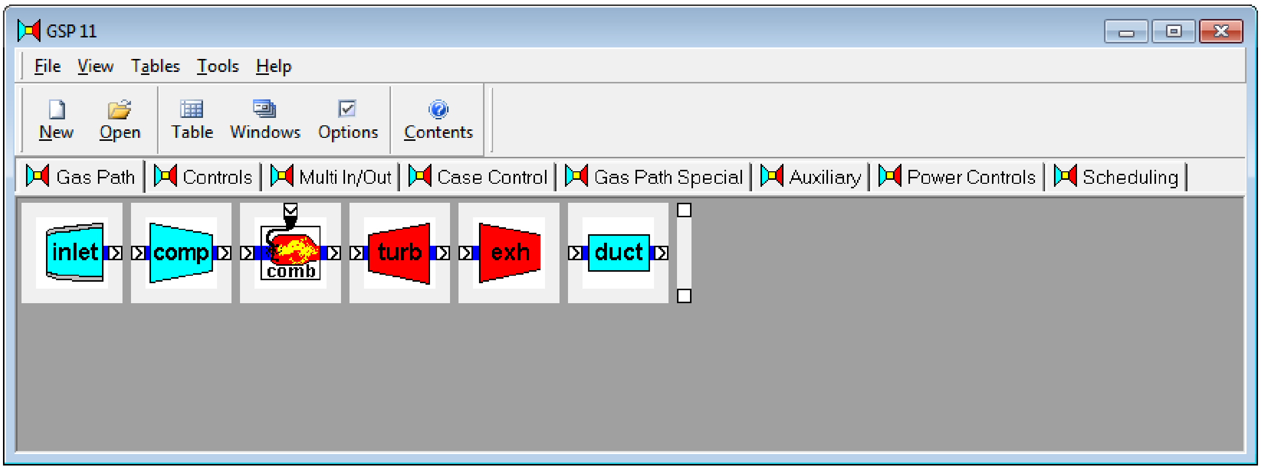
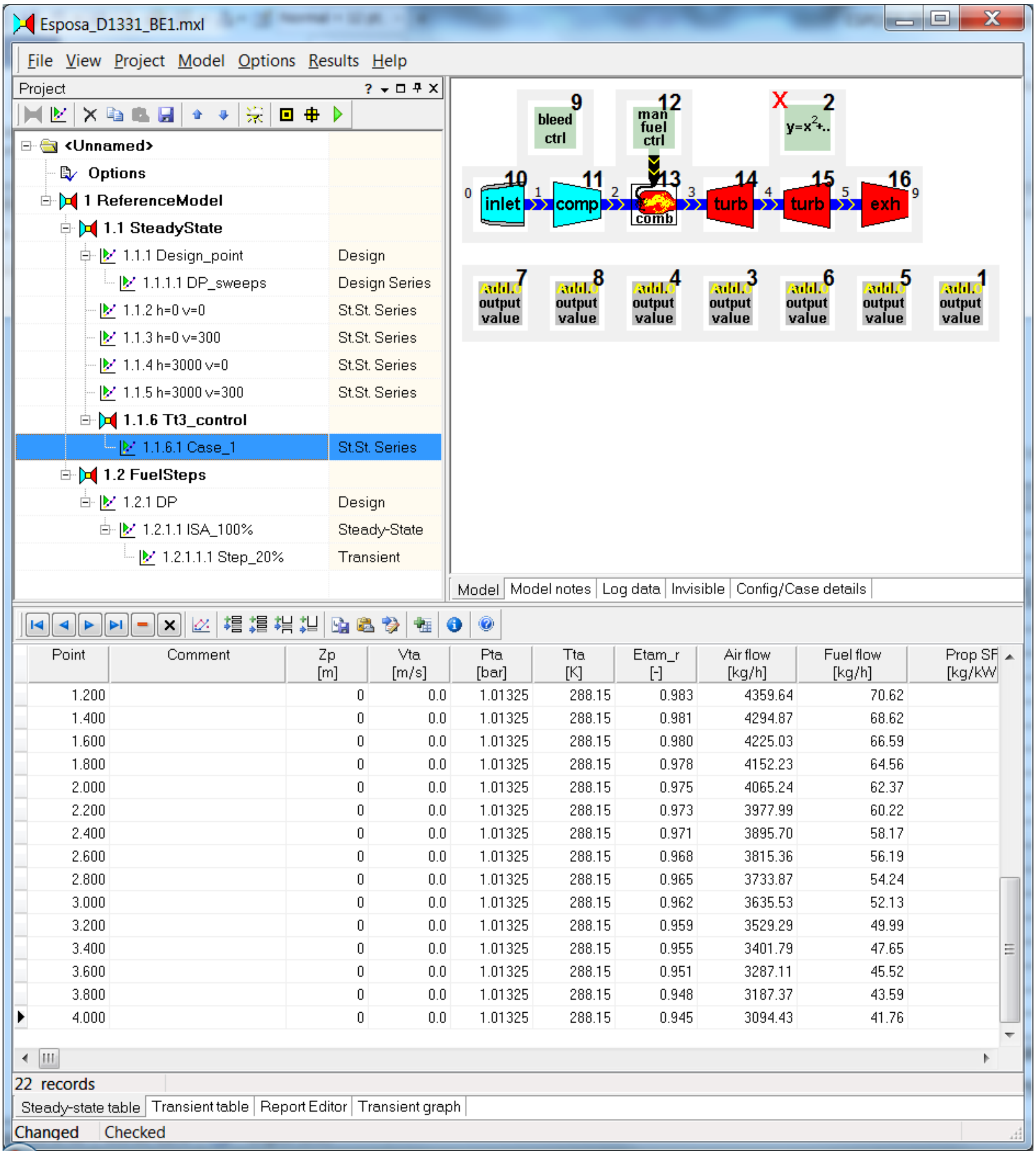


Figure 1 - GSP main window

When opening an existing or a new model, the user is presented with the actual modeling project window (Figure 2). The project window comprises of several windows which can be arranged according to the user's desired view as the project window fully supports docking. In Figure 2, there are 3 windows currently visible in the project window; other windows are either invisible, or stacked behind the visible windows on tab sheets. Currently visible are the project tree (top left), model window (top right), and the results table (bottom). Detailed info on the model can be found on the tab sheets behind the model window and graph windows are found behind the results table window. The project window is composed by several dockable windows and is therefore highly configurable to the modelers needs.



Point	Comment	Zp [m]	Vta [m/s]	Pta [bar]	Tta [K]	Etam_r [-]	Air flow [kg/h]	Fuel flow [kg/h]	Prop SF [kg/kW
1.200		0	0.0	1.01325	288.15	0.983	4359.64	70.62	
1.400		0	0.0	1.01325	288.15	0.981	4294.87	68.62	
1.600		0	0.0	1.01325	288.15	0.980	4225.03	66.59	
1.800		0	0.0	1.01325	288.15	0.978	4152.23	64.56	
2.000		0	0.0	1.01325	288.15	0.975	4065.24	62.37	
2.200		0	0.0	1.01325	288.15	0.973	3977.99	60.22	
2.400		0	0.0	1.01325	288.15	0.971	3895.70	58.17	
2.600		0	0.0	1.01325	288.15	0.968	3815.36	56.19	
2.800		0	0.0	1.01325	288.15	0.965	3733.87	54.24	
3.000		0	0.0	1.01325	288.15	0.962	3635.53	52.13	
3.200		0	0.0	1.01325	288.15	0.959	3529.29	49.99	
3.400		0	0.0	1.01325	288.15	0.955	3401.79	47.65	
3.600		0	0.0	1.01325	288.15	0.951	3287.11	45.52	
3.800		0	0.0	1.01325	288.15	0.948	3187.37	43.59	
4.000		0	0.0	1.01325	288.15	0.945	3094.43	41.76	

Figure 2 - GSP project window showing the BE1 turboprop engine model

3 Development of the BE1 turboprop engine model

3.1. General

The engine model is to be used for advanced steady-state and transient performance prediction purposes. In particular:

- effect studies for cycle optimization (sensitivity analysis) by the OEM,
- fuel step transient simulations for control system development (system identification),
- development and demonstration of gas path analysis concepts (Esposa WP 4.2)

Reference data for the model development are obtained from ref. [2] and [3].

3.2. GSP model configuration

In Figure 3 a cross section drawing of the BE1 engine is given. Note that old station numbering standard is used (1 = compressor inlet, 3 is HP turbine inlet etc.).

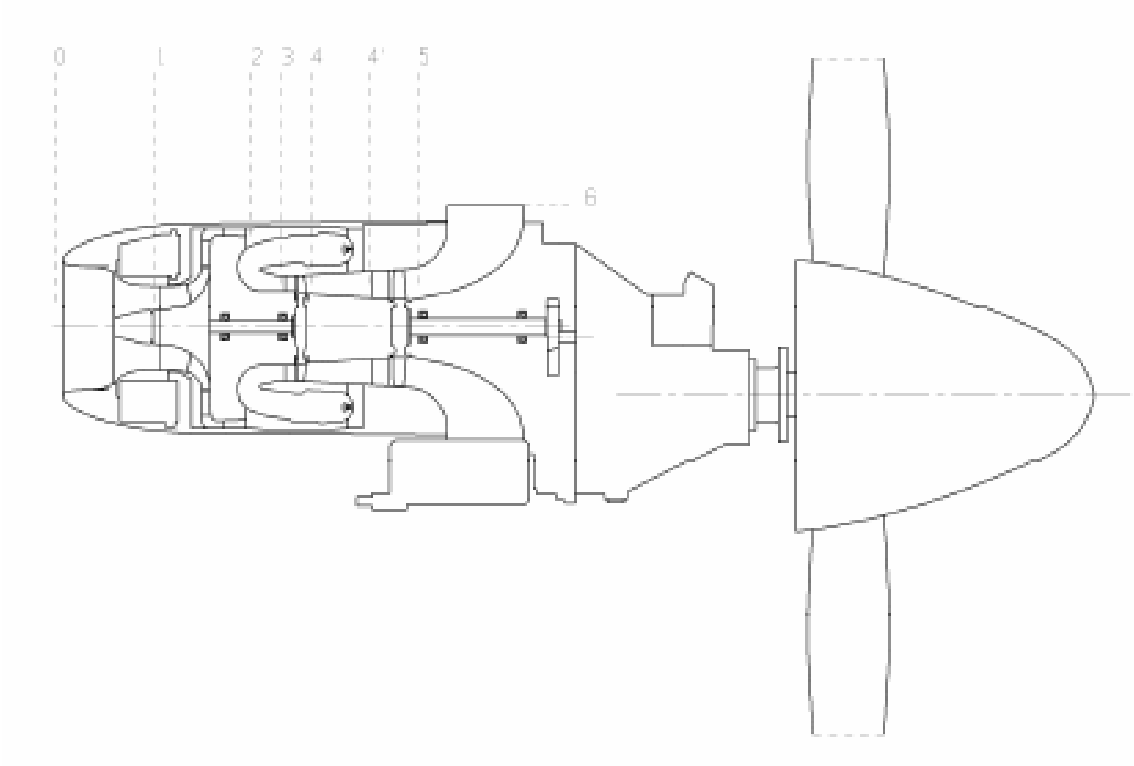


Figure 3 – BE1 engine configuration and station numbering

The BE1 engine is a turboprop engine. This means both shaft power and, depending on the exhaust nozzle configuration, some jet thrust is provided. In GSP this means the power turbine load is specified, taking power from the gas and leaving gas at some pressure level above ambient to expand into a jet. Jet thrust will only be effective for forward thrust of vertical lift to the extent that the jet will be directed backwards or downwards. This aspect however remains outside the scope of the engine performance simulations (but is important for aircraft performance aspects).

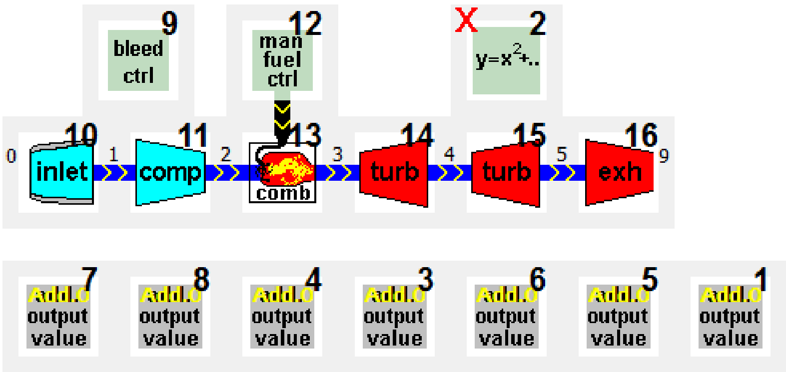


Figure 4 – BE1 GSP model configuration

Figure 4 shows the BE1 model in the GSP modeling environment corresponding to the turboprop cycle configuration. The icons numbered 10 to 16 (the number is depicted in the top right corner of the component block) represent the primary gas path engine components. The gas generator consists of an inlet (10), a compressor (11), a combustor (13) and the high pressure turbine (14). The gas generator exit gas is expanded in the low pressure power turbine (15). In the exhaust nozzle (16) the power turbine exit gas which still has some over pressure is expanded into a jet at the nozzle exit station 9, providing some thrust. Since there is no divergent nozzle part nozzle throat station 8 is equivalent to exit station 9 in the GSP model. The next step is to configure the component models by double clicking the icons after which component data and performance characteristics can be specified corresponding to design/reference or measurement data.

3.3. Performance data

The GSP model has been prepared using the following performance data:

- A limited number of operating point data sheets from PBS performance deck obtained from ref. [2]
- Scaled compressor and turbine maps from other sources:
  - for the compressor, the actual component map from [8] was used.
  - for the gas generator turbine the standard generic GSP map was scaled
  - for the power turbine, the map of the similar (but larger) Esposa BE2 engine power turbine obtained from [3]

Table 1 shows an overview of the performance ratings taken from ref. [2]. It contains the power setting corresponding to the corrected (reduced[3]) gas generator speed. Note that each rating includes details of the primary gas flow path; e.g. pressures and temperatures at the engine stations/component interfaces. These data are shown graphically in the validation graphs given in appendix A. The data points have been used to create a tuned model of the BE1 engine by adjusting the specific data inputs in the data entry windows of the GSP model component icon (in GSP, double click on icons as shown in Figure 4 to edit the component properties).

H [m]	V [km/h]	Power setting Nc%_gg (%corrected gas generator speed) Turbine shaft power [kW]								
0	0	106 %* 204 kW	102 % 204 kW	100 % 195 kW	97.5 % 170 kW	95 % 144 kW	90 % 101 kW	85 % 70 kW	80 % 47 kW	53 %* 7 kW
0	300	106 %* 217 kW	102 % 217 kW	100 % 213 kW	97.5 % 186 kW		90 % 111 kW	85 % 77 kW	80 % 51 kW	53 %* 7 kW
3000	0	106 %* 160 kW	102 % 142 kW	100 % 130 kW	97.5 % 113 kW	95 % 97 kW	90 % 67 kW	85 % 46 kW	80 % 30 kW	
3000	300	106 %* 172 kW	102 % 158 kW	100 % 143 kW	97.5 % 125 kW	95 % 106 kW	90 % 74 kW	85 % 51 kW	80 % 33 kW	53 %* 5 kW

Table 1 – PBS provided performance operating points of the BE1 engine

[3] Reduced to ISA - (101325 Pa, 288.15K)

* The 106% rating data in Table 1 are suspect (the sea level data sheets provided by [2] for 102% and 106% were identical which indicates inconsistency) and have therefore not been used for validation. The three 53% (IDLE) data points were also not used for validation in view of the absence of the real maps in the model making model prediction of IDLE power very difficult if not impossible.

3.4. Power setting parameter

The PBS engine performance data uses % gas generator corrected speed Nc%gg as the power setting variable. This practice is adopted here and also GSP model is configure with the power setting in terms of Nc%gg. 100% is equivalent to 56500 rpm. As a result, off-design power setting specification is done using an equation component adding an equation in order to calculate fuel flow for a given Nc%gg value. Figure 5 shows a screenshot of the GSP Ncgg%control power setting equation component.

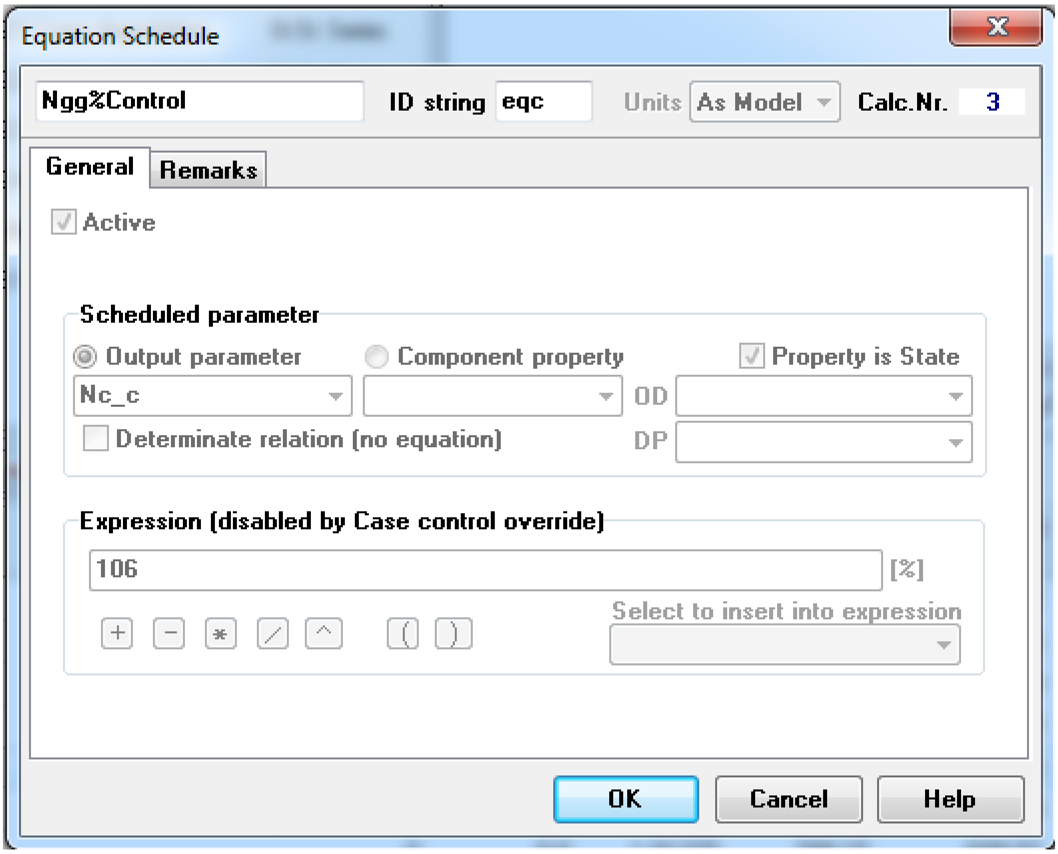


Figure 5 – Nc corrected compressor speed control equation component data entry window

3.5. GSP Design point

For the GSP model, a design point (or cycle reference point) must be defined which serves as a reference point for subsequent off-design steady-state and transient simulations in the solver (see ref. [1]). Table 2 shows the design point performance data selected: 100% gas generator speed at ISA conditions.

Inlet pressure Pt1	101325	[N/m2]
Inlet temperature Tt1	288.15	[K]
Nc%gg gas generator speed	100	[%]
Inlet mass flow W2	1.424	[kg/s]
Compressor isentropic efficiency	0.805	[−]
Compressor pressure ratio	4.679	[−]
Fuel mass flow	0.0261	[kg/s]
Combustion efficiency	NOT GIVEN	
Fuel lower heating value Hv	42.916	[MJ/kg]
Gas generator speed	56500	[rpm]
Gas generator turbine isentropic efficiency	0.836	[−]
Power turbine isentropic efficiency	0.825	[−]
Shaft mechanical efficiency (both shafts)	0.99	[−]
Power turbine power delivered	195.12	[kW]

Table 2 – GSP Design point data

These data are entered in the ‘Design’ tab sheet data fields of the GSP component models shown in Figure 4. Figure 6 shows an example of the compressor design sheet.

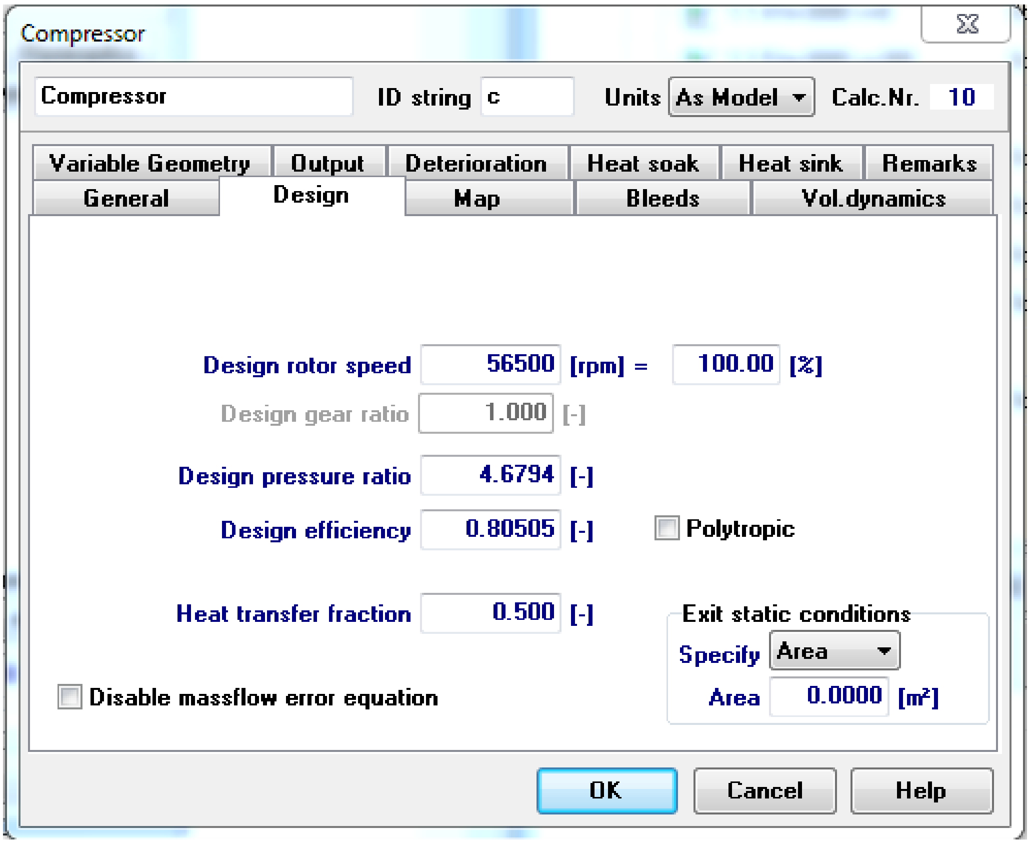


Figure 6 – Compressor data entry window showing design data sheet

3.6. GSP off-design (OD) data

3.6.1. Turbomachinery

GSP model off-design performance is primarily determined by the turbomachinery component characteristics. For the GT and PT the scaled maps are used and for the compressor map the actual map is used.

3.6.1.1 Compressor Characteristics

PBS supplied the real compressor map with appropriate coordinates acceptable to the standards permitted by gas turbine performance software, under the condition that “these characteristics are proprietary (acceptable only in dimensionless form) and may not be provided to companies other than VZLU, UNIS”.

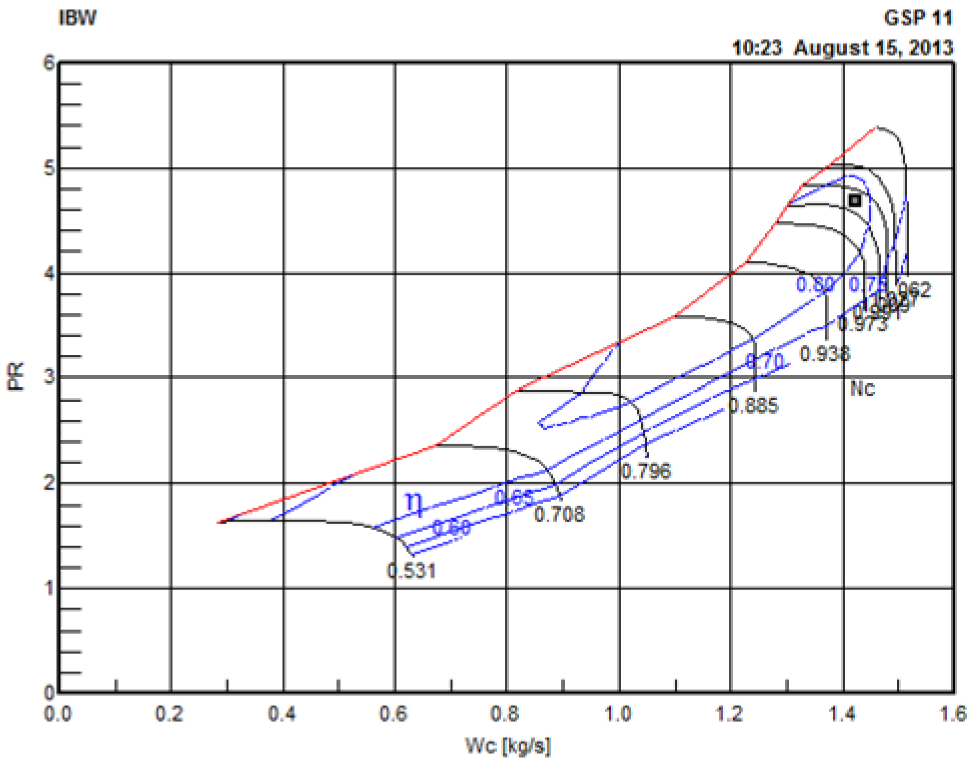


Figure 7 – Actual Compressor map

The turbomachinery maps are specified in the 'Map' tab sheets of the compressor and turbine data entry windows. Important is the location of the map design point that coincides with the engine design point and is used the scale the map for off-design simulation. In the graphs above these are indicated by the little yellow rectangles. .

3.6.2. Turbine Characteristics

The real turbine characteristics have not been validated by PBS. The map format/coordinates have been transformed and tested by the TUD but did not result in a better model match. In future correspondence turbine maps will be improved by incorporation of:

- PT outlet system pressure loss in order to match brake measured shaft power.
- Data from altitude chamber in CIAM, on which further PT characteristic "tuning" will be possible.

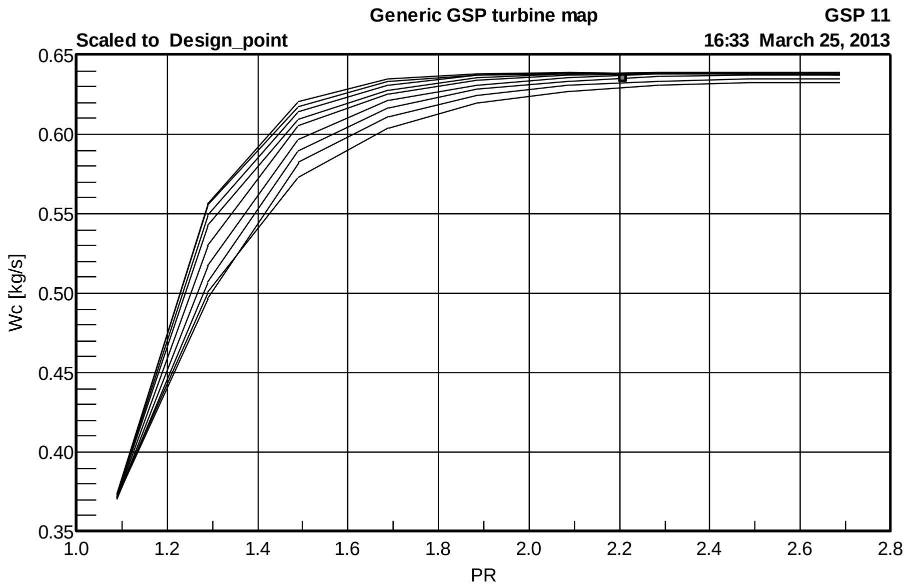


Figure 8 – Gas generator turbine map, scaled from generic GSP turbine map

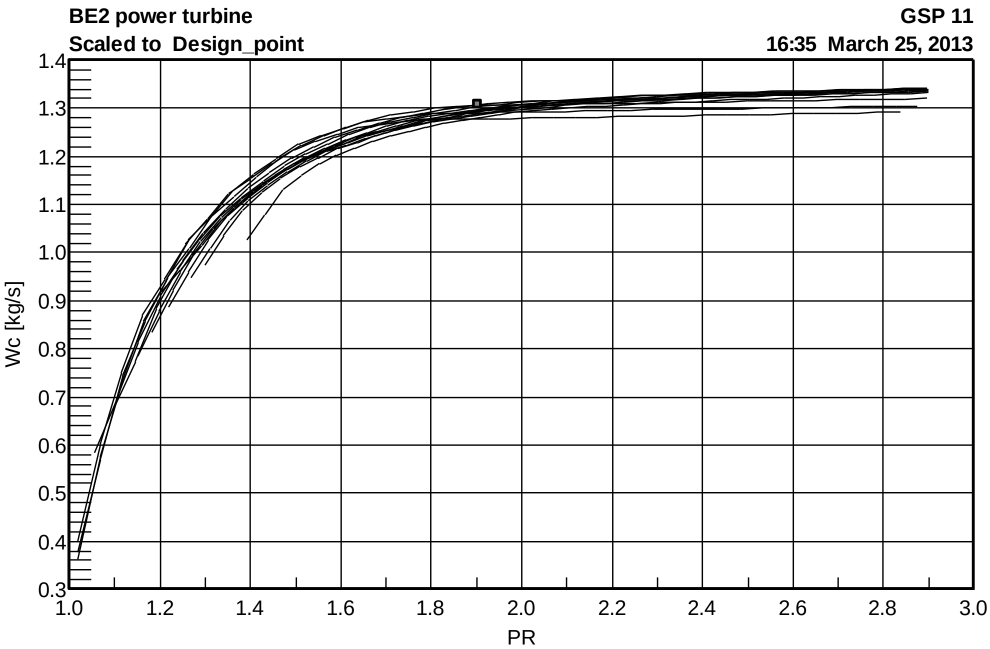


Figure 9 – Power turbine map, scaled from BE2 power turbine map

At this point in time the generic maps (figure 8 and 9) will continue to be used until the characteristics have been better finalized by PBS.

3.6.2.1 Map Format Transformation

PBS traditionally uses coordinates of map characteristics with non-dimensional groups such as:

$$f(\frac{U}{C_s}, PR_t, \eta_{tt}, W_t) = 0$$

The format of the dimensional groups thus needs to be transformed into a more commonly accepted group of parameters used with axial technology:

$$f(N_c, PR_t, \eta_{tt}, W_t) = 0$$

A transformation method has been defined and a standard format communicated with PBS. The method assumes constant CP and GAMMA. For the range of TIT temperatures there will not be much variation and thus the error induced is small. The values used in the calculation for both turbines are 1158.3 J/kg/K and 1.33.

The other components have simpler characteristics:

3.6.3. Inlet

The inlet only has ram recovery (or pressure loss) as a variable affecting performance. Separate DP and OD pressure loss can be specified. Although complex relations of ram recovery can be given as functions of flight Mach number and/or corrected inlet mass flow, for the BE1 engine no pressure loss (ram recovery RR = 1) is given corresponding to the uninstalled PBS data without inlet pressure loss. Of course, effects of inlet pressure loss can be analyzed easily adapting the off-design ram recovery factor inlet data entry window using the `User specified PR` option (Figure 10). With the `User specified PR design only` option only DP pressure loss is given and OD pressure loss scaled with mass flow using the theoretical relation dp/p ~ (Wc/Wc_des)^2.

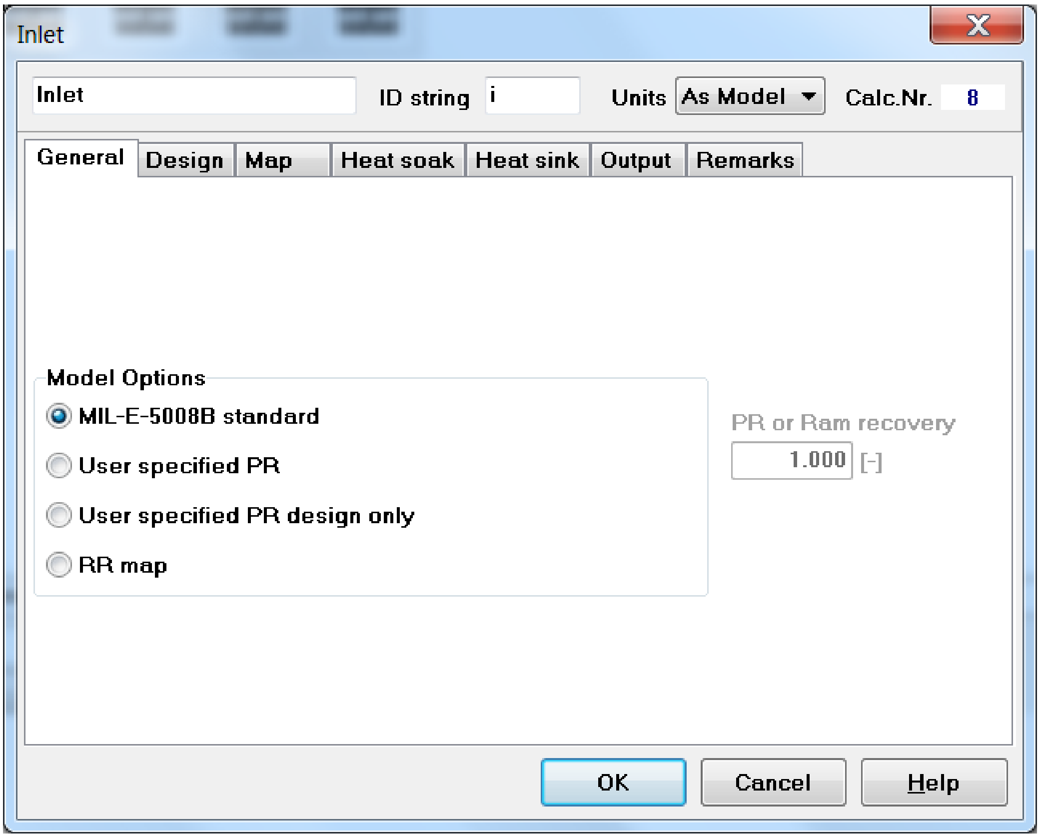


Figure 10 – Inlet data entry window.

3.6.4. Combustor

For the combustor both pressure loss and combustor efficiency can be given as shown in Figure 11. In the design point (DP) a 94% combustor efficiency is given and a 2% pressure loss is given. This unusually low value is discussed in section 4.3. OD relative pressure loss is scaled to Wc^2 as in the inlet.

3.6.5. Shaft mechanical losses

Both the gas generator and power turbine shafts have 99% mechanical efficiency, which is specified in the attached turbine data entry sheet.

3.6.6. Exhaust nozzle

Exhaust nozzle losses can be expressed in velocity and thrust coefficients. A relatively low velocity coefficient of 0.643 and a thrust coefficient of 0.97 are given to represent the losses in the nozzle (see Figure 12). Discharge coefficient CD has no effect on the calculations for a fixed nozzle and remains 1.0.

3.6.7. Ducts

As no data we available on pressure or other (e.g. thermal) losses in interconnecting ducts, no duct components have been used for the BE1 GSP model.

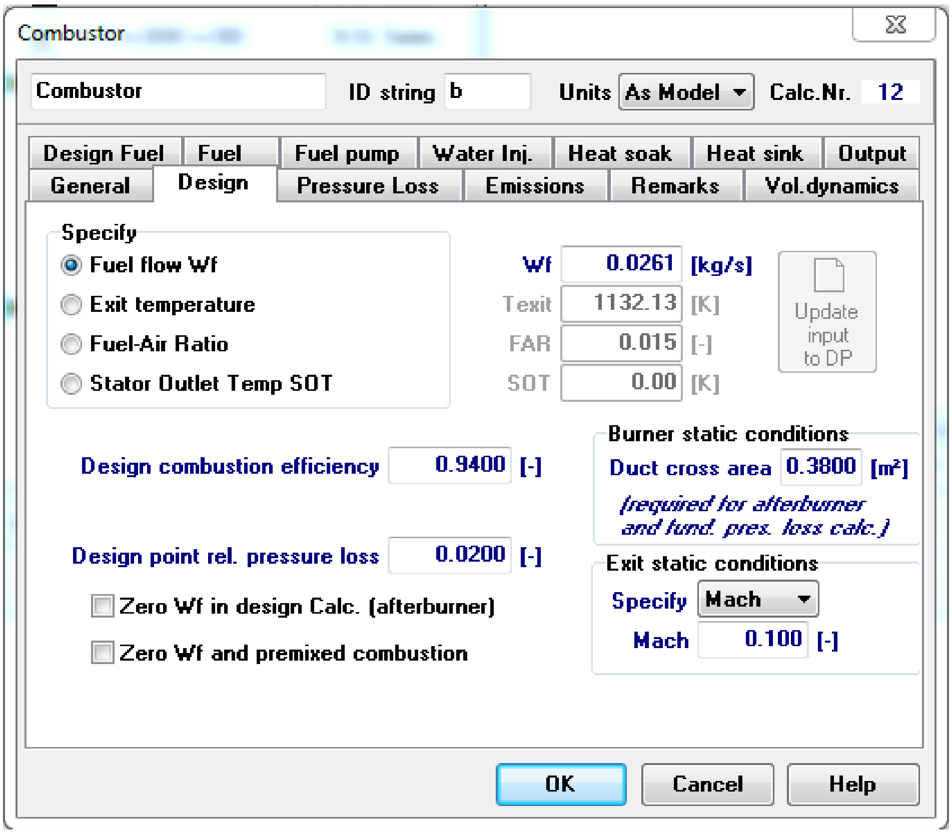


Figure 11 – Combustor data entry window (design tab sheet)

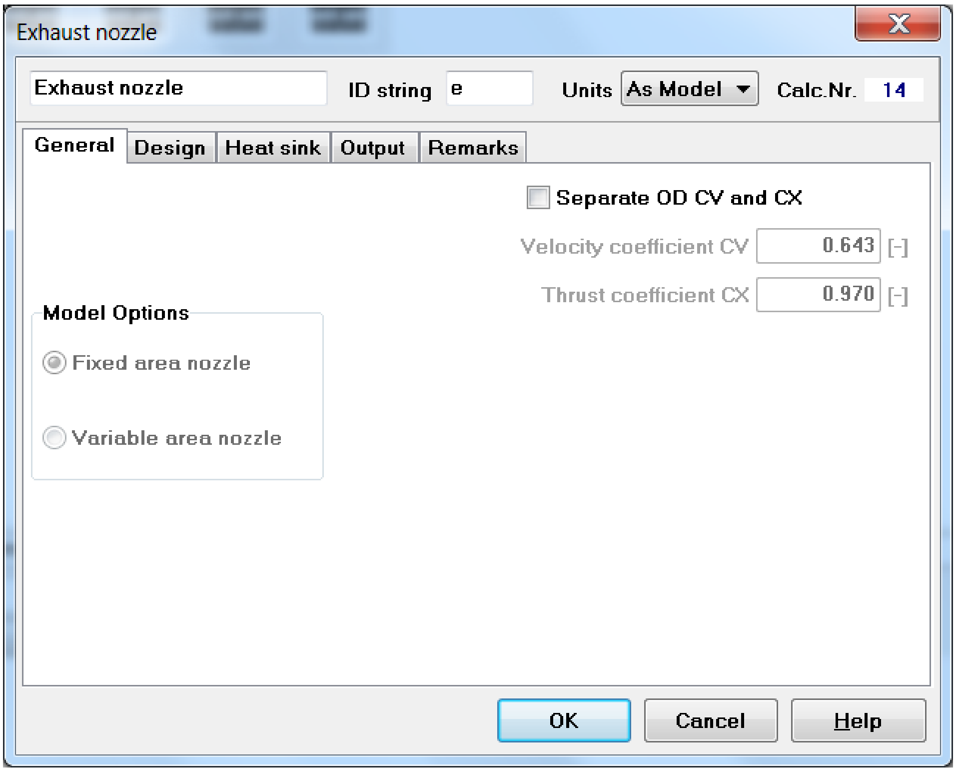


Figure 12 – Exhaust nozzle data entry window

3.7. Heat transfer effects

With the small size of the BE1 engine, heat transfer and loss effects may become significant, including compressor performance degradation do to heat coming from the hot parts. However, since detailed engine data en test results are required to extend to model with heat transfer effects, this is omitted at this stage.

3.8. Model tuning

Once all the data are entered in the component's data entry windows, simulations can be run to compare the results to the data from ref. [2]. Usually an iterative process is required to increase the model data output values by adjusting uncertain or unknown component performance characteristics within the uncertainty margins.

With the above data, the GSP model is configured and model output data subsequently evaluated against given data, first in the design point and next in the off-design points given in Table 1.

Design point tuning is done by adapting the unspecified data such as pressure losses, unknown efficiency etc. in order to match all GSP results to the specified engine performance parameter values of the specific operating point assigned at GSP design point.

Off-design tuning is subsequently performed by adapting map design points (and the maps themselves if necessary,) and off-design loss and efficiency relations. For the BE1 model, the maps themselves did not need adaptation.

In section 4 results of the model tuning procedure are given.

4 Model validation

4.1. Design point match

In Table 3 the GSP design point data obtained after tuning are compared with PBS data.

Parameter	Unit	PBS data	GSP value	% error
N	[%]	100	100	0%
PW_{shaft}	[kW]	195.12	193.24	0.9%
PW_{prop}	[kW]	192.42	192.58	0.08%
sfc	[kg/kW/h]	0.487	0.488	0.21%
FN	[N]	180.13	182.99	1.59%
c_9	[m/s]	128.62	130.09	1.14%
W2	[kg/s]	1.424	1.424	0.00%
η_c	[-]	0.805	0.805	0.00%
η_{gg}	[-]	0.836	0.836	0.00%
η_{pt}	[-]	0.825	0.825	0.00%
Pt_1	[N/m2]	101325	101325	0.00%
Pt_2	[N/m2]	474138	474140	0.00%
Pt_3	[N/m2]	464493	464657	0.04%
Pt_4	[N/m2]	208913	210299	0.66%
Pt_5	[N/m2]	108568	110426	1.71%
Tt_1	[K]	288.15	288.15	0.00%
Tt_2	[K]	484.68	484.71	0.01%
Tt_3	[K]	1132.13	1133.53	0.12%
Tt_4	[K]	965.69	954.89	-1.12%
Tt_5	[K]	846.84	838.05	-1.04%
Tt_9	[K]	846.84	838.05	-1.04%

Table 3 – Design point validation

The result is a maximum 2% deviation from PBS given design point data.

4.2. Off-design point performance match

In Appendix A, graphical representations of the off design model match are shown for the operating conditions given in Table 1.

4.3. Validation discussion

The result is a maximum 2% deviation from design point and maximum 5% deviation from off-design performance data. Percentages are relative to design point parameter values. This is well within range for sensitivity and effect study analysis and a demonstration of gas path analysis GPA (Esposa WP 4.2).

After reconfiguring the models with the actual turbine component maps at PBS, more accurate match can be obtained.

A conflict seems to emerge at the combustor energy balance: a match with PBS design performance data could only be obtained with a combustor efficiency of 94%. This is unusually low and therefore the origin of this conflict must be resolved. With the small engine size a possible explanation could be heat loss, but then still 6% heat loss is hard to imagine. Possibly, the PBS cycle model combustor energy balance is differently calculated (GSP uses a chemical enthalpy reactor model, based on the NASA CEA program ([4], [5]) which is more accurate than simple averaged specific heat (Cp) based combustor temperature rise calculations). Alternatively, heating value definitions are deviating or other differences may be at the origin.

5 Parameter studies

The model for the BE1 engine can be used for parameter effect studies. This implies that we can slightly alter several parameters and assess the effects on the overall engine performance.

5.1. Model case input

Effect studies can be performed very easily with the use of case input component blocks (“Case Control” component library of the GSP main window). Every case model can be easily turned into a model to assess parameter variations. The two components called ‘Manual case control’ and ‘Loop case control’ can be used for these parameter effect studies. The ‘Loop case control’ component is able to create looped parameters data, nesting up to three parameters very quickly. If the modeler requires more parameter effects, the ‘Manual case control’ component can be used. The latter component can schedule an infinite amount of parameters. The only drawback is that the data is not nested; this is left to the user to do (in contrary to the ‘Loop case control’ component which creates the nested loops automatically). It is advised to use a third party spreadsheet program to create the loops outside GSP, and copy the data back into the ‘Manual case control’ component (copy and paste actions are supported in the case input grids). Drag and drop the component of your interest onto the model window of a run case or a model configuration and configure the component to your needs.

Effect studies can be done for design and for off-design model cases. Design effect studies can aid in determining the correct gas turbine cycle for a specific application while off-design effect studies can aid in determining the sensitivity to certain parameters and what the impact is on the current design.

5.2. Parameter study examples

The following examples will demonstrate the capabilities of the GSP parameter variation. The first example demonstrates the use of parameter variation in the (preliminary) design process of a gas turbine, while the second example shows the impact of parameter variations on the performance of an existing cycle using different loss effects.

Naturally, these examples also apply to the BE2 engine design [6]. And also for the BE2 engine a number of different GSP parameter study examples are given which may also apply to the BE1 engine.

5.2.1. Design point performance analysis

During cycle design optimization, one important combination of parameters to be selected is cycle pressure ratio PR_c and turbine inlet temperature Tt3. Effects on power and cycle efficiency can be easily analyzed using a DP parameter design sweep specified by a Loop case controller. An example for the BE1 engine is given in Figure 13.

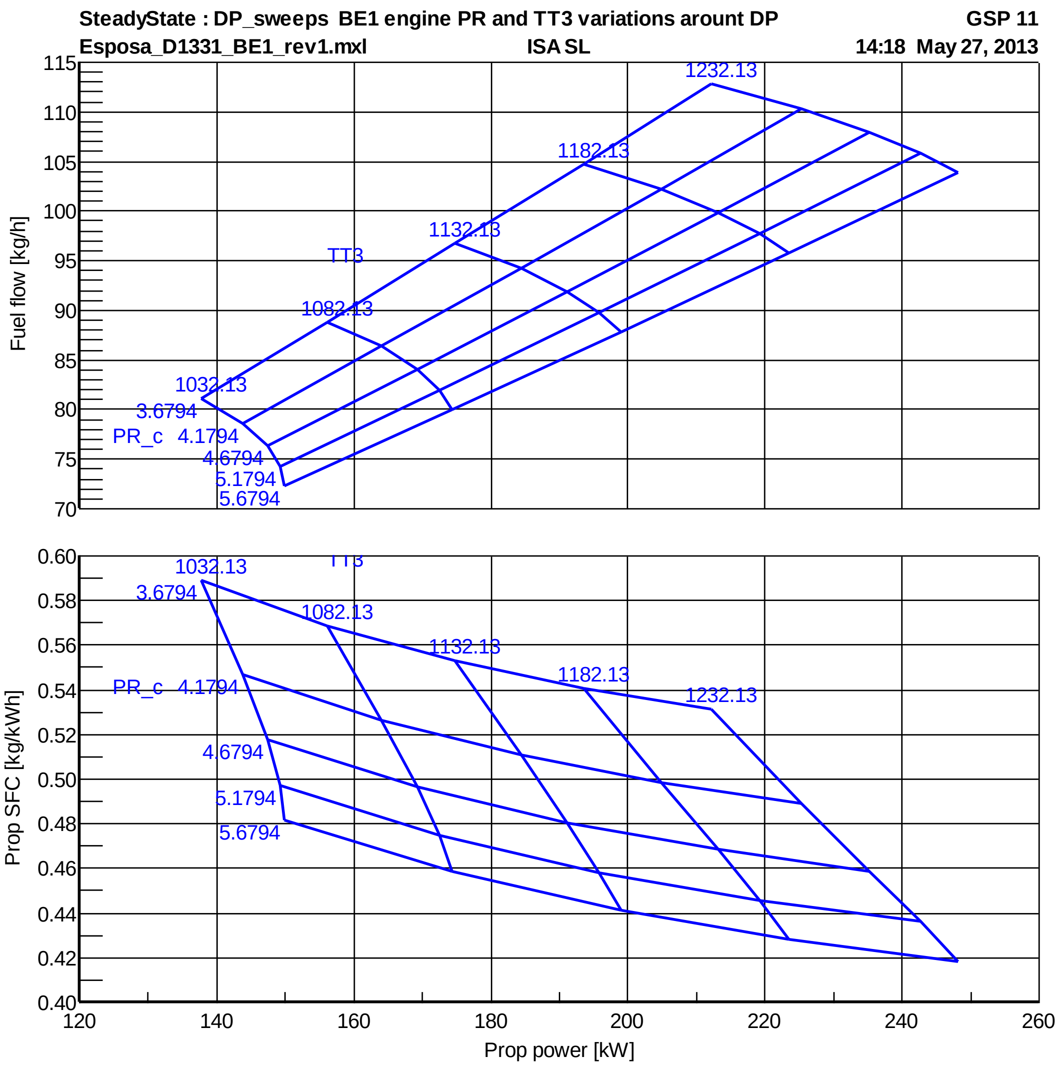


Figure 13 –Variation of BE1 engine DP cycle pressure ratio PRc and Tt3.

In Figure 13 design point SFC and fuel flow WF are shown versus Propeller power for varying PR_c and Tt3 in carpet plots. The carpet plot option in GSP is particularly useful for gas turbine cycle and conceptual design analysis.

5.2.2. Off-design performance analysis

A common off-design effect study is analyzing the effect of compressor customer bleed flow rate that is required for the aircraft cabin air conditioning system for example. Figure 14 shows the effect of 10% compressor bleed (taken at compressor exit) on performance. The ‘D’ in the plot indicates the design point. Black is reference (no bleed) performance. Red dashed is 10% bleed flow. Turbine entry temperature Tt3 is varied as input parameter in this case since it represents a maximum performance limiter. ITT is added to see the effect on the parameter used by the control system to determine thermal load on the hot section. In Figure 15 the effect on the compressor operating line is shown.

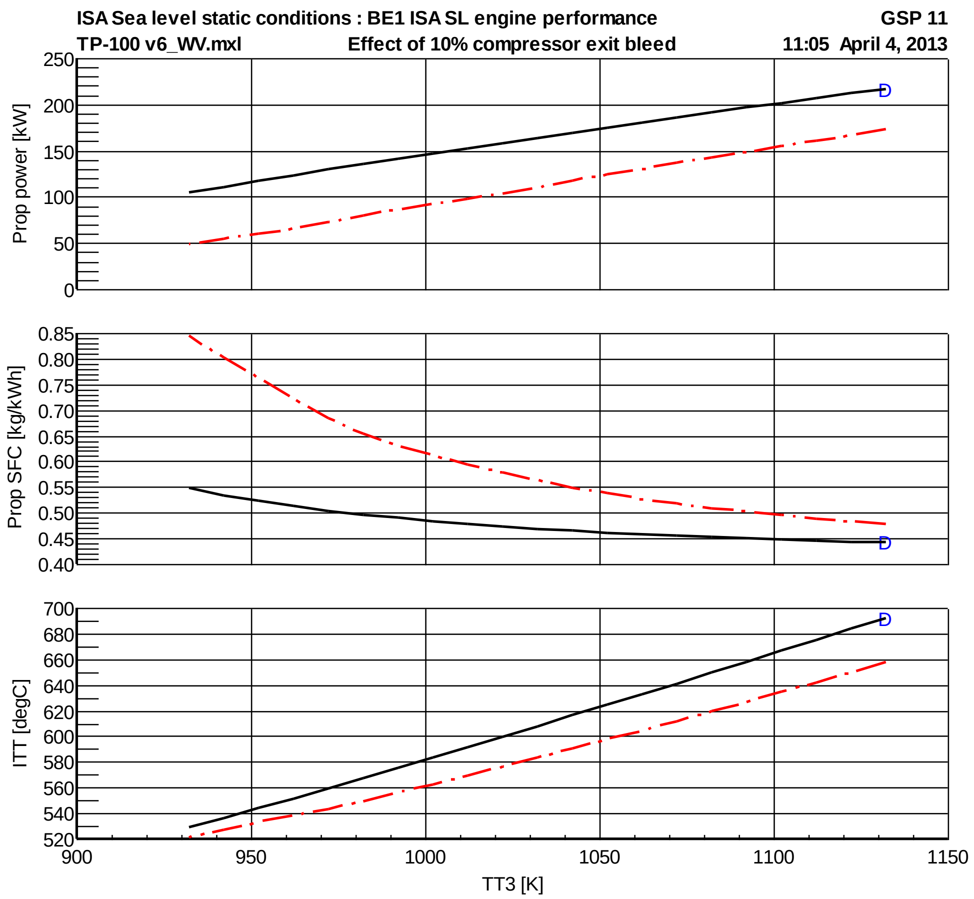


Figure 14 – Example of off-design analysis: effect of 10% compressor bleed

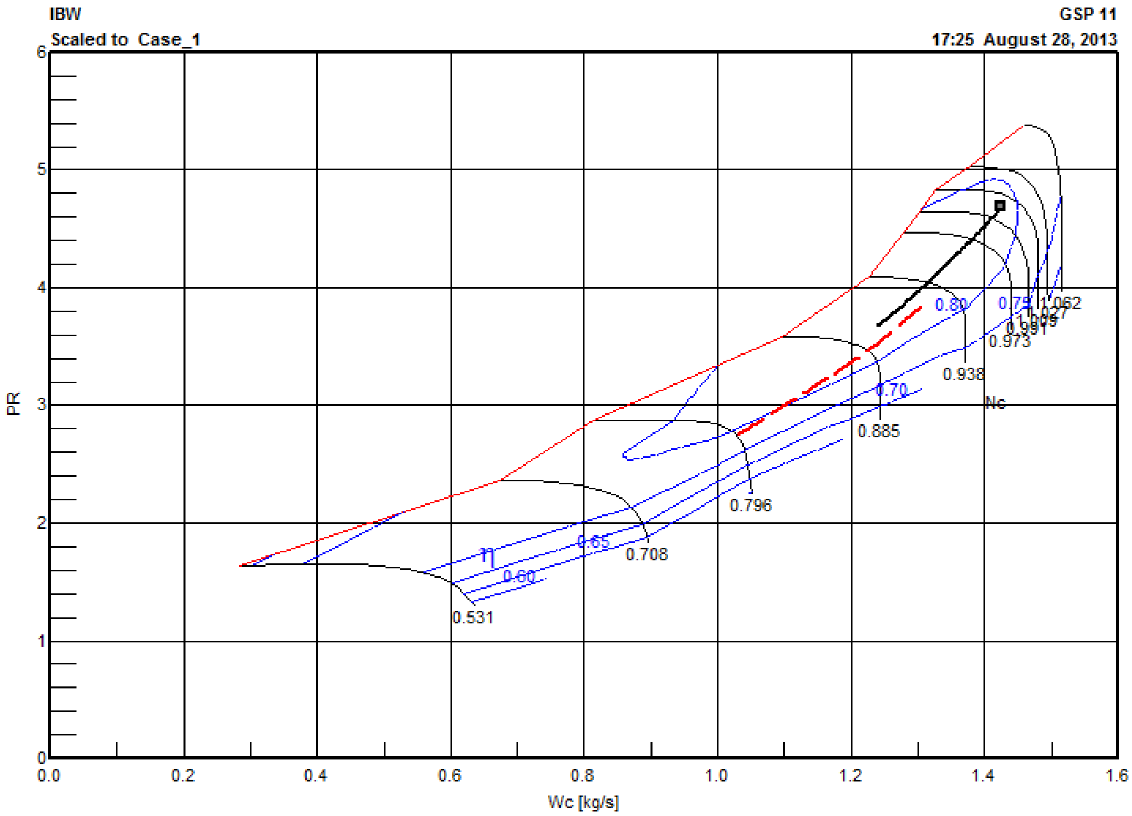


Figure 15 – Example of off-design analysis: effect of 10% compressor bleed on compressor map operating curve

6 Transient studies

6.1. General

The model for the BE1 engine can also be used for transient effect studies. This implies that dynamic effects are taken into account on the overall engine performance. The transient effects that can be included in GSP are rotor inertia, volume and heat soakage effects and, if control system models are added, control system schedules, PID control loops and dynamics. Rotor inertia, directly affecting rotor speed acceleration rates, usually is the dominating factor for transient performance. Volume effects may be calculated for each gas path component but often are relatively small and therefore disabled. With the small size, heat soakage effects may become significant. However, since detailed engine data and test results are required to extend the model with heat soakage effects, this is omitted at this stage.

6.2. Fuel step transients for system identification

As the model is to be used for control system design including system identification, a number of examples are given which show how to generate transient responses of control parameters such as gas generator rotor speed and gas generator exit temperature ITT to fuel flow steps. Propeller and thus free power turbine speed are assumed constant, gas generator spool inertial moment is assumed 0.0076 kgm2.

The blue solid curves in Figure 16 show the response to a -20% followed by a +20% step in fuel flow. The top graph shows the WF input step function. The response is given of N%gg, TT3 (to assess effect on turbine entry thermal load) and WFP3 (i.e. WF/P3). The responses of all other parameters can be given easily by changing the graph output parameters in GSP. Also, the procedure can easily be repeated at other operating conditions (power setting, inlet conditions) to account for the severe non-linearity of gas turbine performance in operating point dependent gain schedules.

The response of the compressor operating point can also be easily generated, see the blue curves in Figure 17..

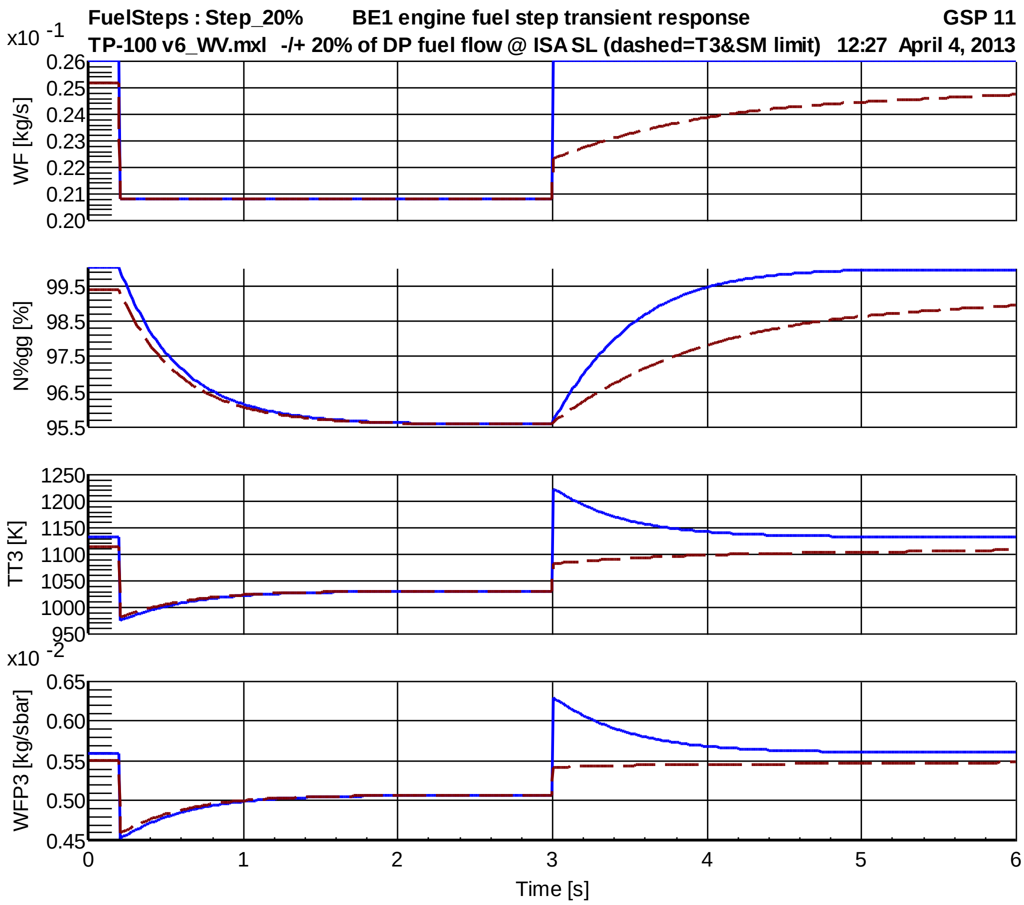


Figure 16 – BE1 engine transient performance response to -/+20% fuel step. The red dashed curve represents the response with a 1% stall margin limit and TT3 limited to 1133 K.

6.3. Generation of control system schedules

Using limiters for temperature and stall margin, the transient generated in section 6.2 can be adapted to an ideal fuel flow input schedule, avoiding all undesired exceeding of limits. The red dashed curves in Figure 16 and Figure 17 show the responses if TT3 is limited to 1133 which is just beyond the design value of 1132 and stall margin is kept above 1%. Interesting to see in Figure 17 is that the limiter even inhibits design performance here since it’s stall margin is just below 1% (0.48% due to the scaled map as discussed above).

The limiter clearly affects fuel flow at the acceleration starting at time = 3 s. For the control system development, the WFP3 response is of particular interest as it represents the maximum acceleration WFP3 schedule that maintains Tt3 and stall margin limits. When plotting WFP3 to N%gg for example (not shown here) a max acceleration WFP3 – Ngg speed schedule can be directly derived for this operating condition.

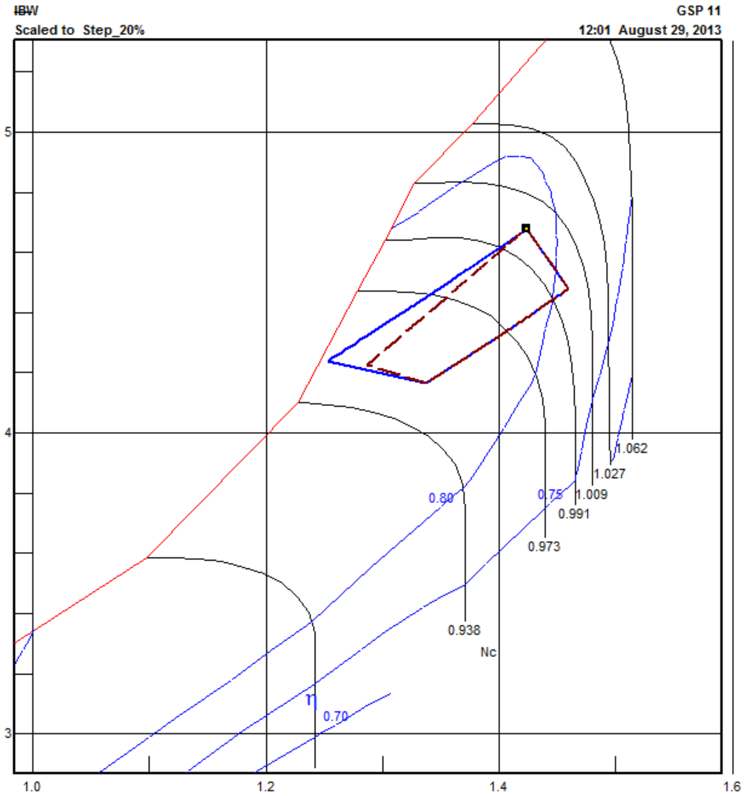


Figure 17 – BE1 engine compressor operating point response to -/+20% fuel step. The red dashed curve represents the response with a 1% stall margin limit and TT3 limited to 1133 K.

6.4. Control system performance evaluation

Once a control system concept has been designed including schedules, PID gains and other logic, a GSP control system model can be developed to simulate transient performance with the control system in the loop. Depending on the complexity of the control system this would require more or less code development work. For simple WF/P3 based gas generator speed / flat rated control, generic GSP control system component models can be used as demonstrated in the TSHAFT.mxl sample project that comes with the GSP installation.

7 Conclusions

The GSP model is sufficiently accurate to perform trade-off (effect/sensitivity) studies for the engine development program. The real compressor map has been supplied by PBS and implemented in revision 2.0 of the deliverable. Off-design comparisons have improved with respect to the previous results and can be seen by the air mass flow results validation on page 43. For simulations that require higher accuracy, the real turbine maps should be implemented in the GSP models. This relatively simple task can be performed by the model end user (engine OEM) after which absolute performance prediction accuracy will be higher, making model suitable for control system design, including stall margin assessments, system identification, control schedule evaluation/optimization and other analysis work.

References

[1] W.P.J. Visser and M.J. Broomhead, 'GSP, A Generic Object-Oriented Gas Turbine Simulation Environment', ASME-2000-GT-0002

[2] TP100 engine deck generated data received by e-mail from Mr. Ing. Jaromir Lamka, CSc. (lamka@vzlu.cz) 22 October 2012.

[3] BE2 engine component maps in GSP / MTU map text file format from Esposa deliverable D.1.3.3.2..

[4] Gordon S., McBride B.J., 'Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications. I. Analysis', NASA Reference Publication 1311, National Aeronautics and Space Administration, Lewis Research Center Ohio, 1994

[5] McBride B.J., Gordon S., 'Computer Program for Calculation of Complex Chemical Equilibrium Compositions and Applications. II. Users Manual and Program Description', NASA Reference Publication 1311,

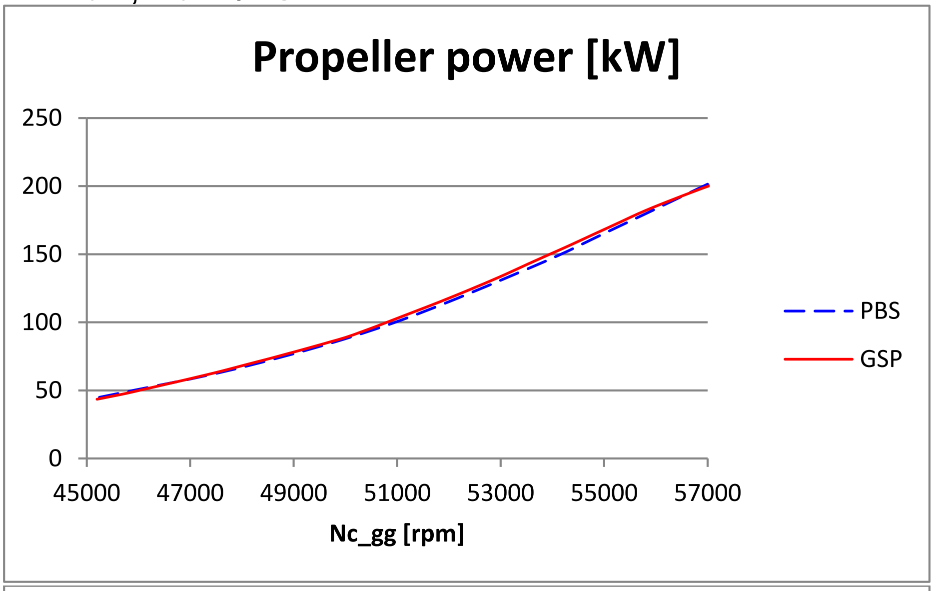
[6] Kogenhop, O. 'BE2 engine performance modeling, Model development with the Gas turbine Simulation Program (GSP)', Esposa deliverable D.1.3.3.2.

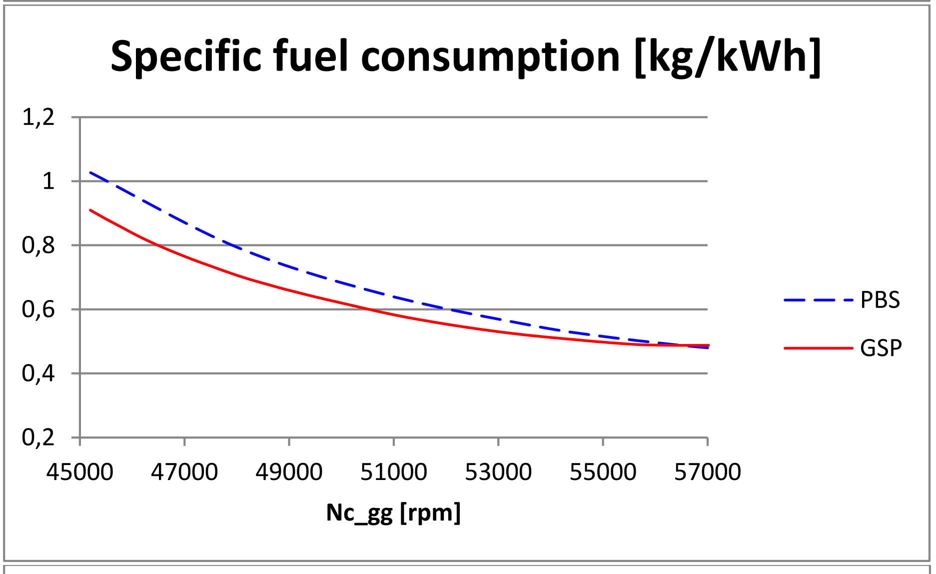
[7] GSP project file Eposa_D1331_BE1_rev2.0.mxl (provided in digital format).

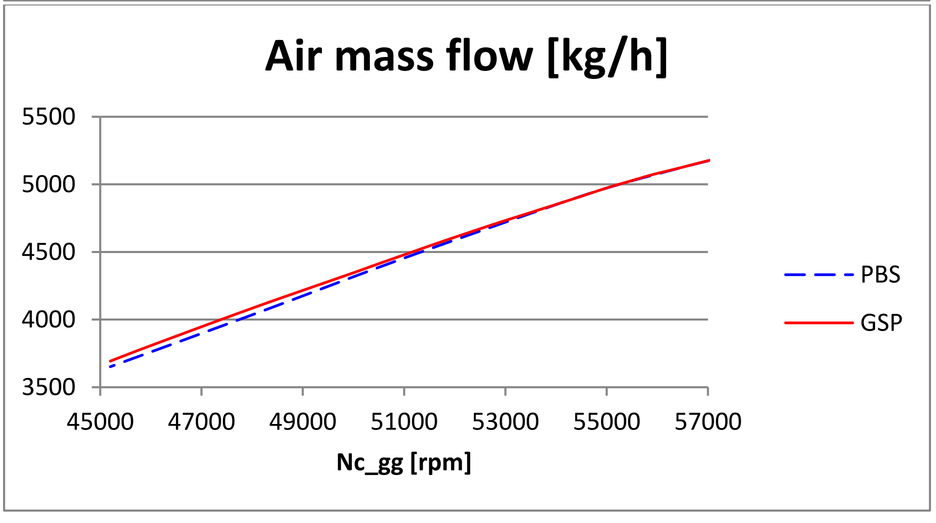
[8] Map Characteristics received by e-mail from Zdeněk Palát. (palat.zdenek@pbsvb.cz) 31 May 2013.

Appendix A Off-design validation results

A.1 h=0 m, v=0 km/h ISA







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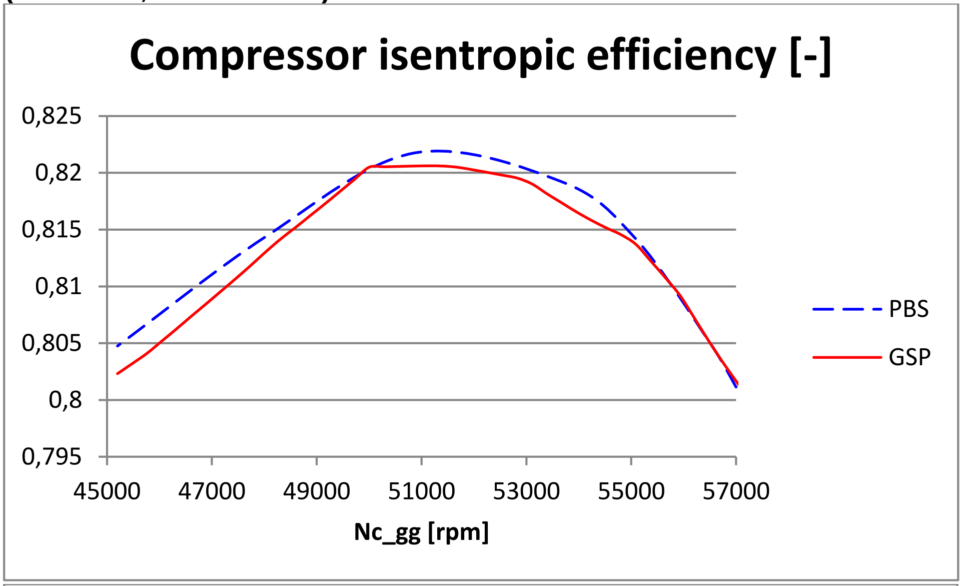

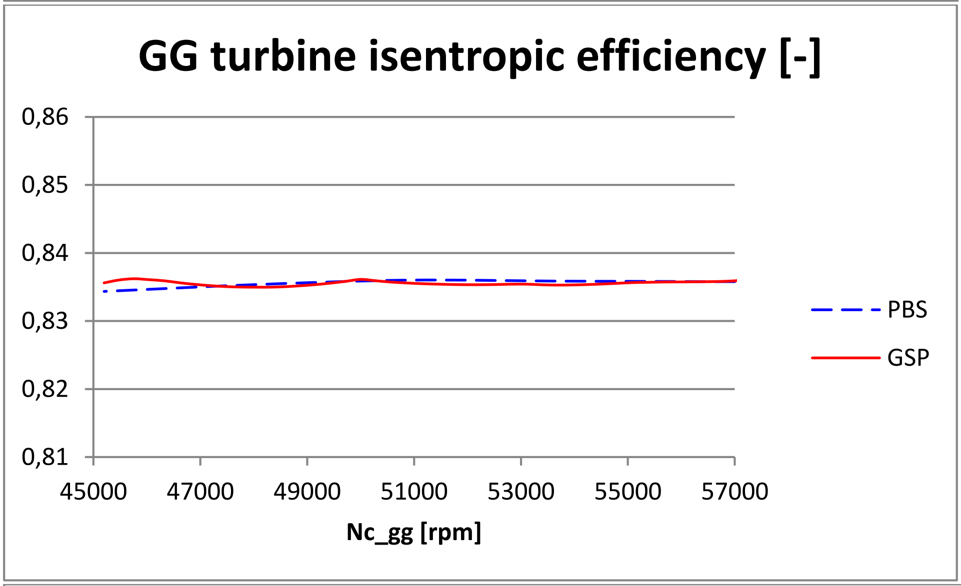

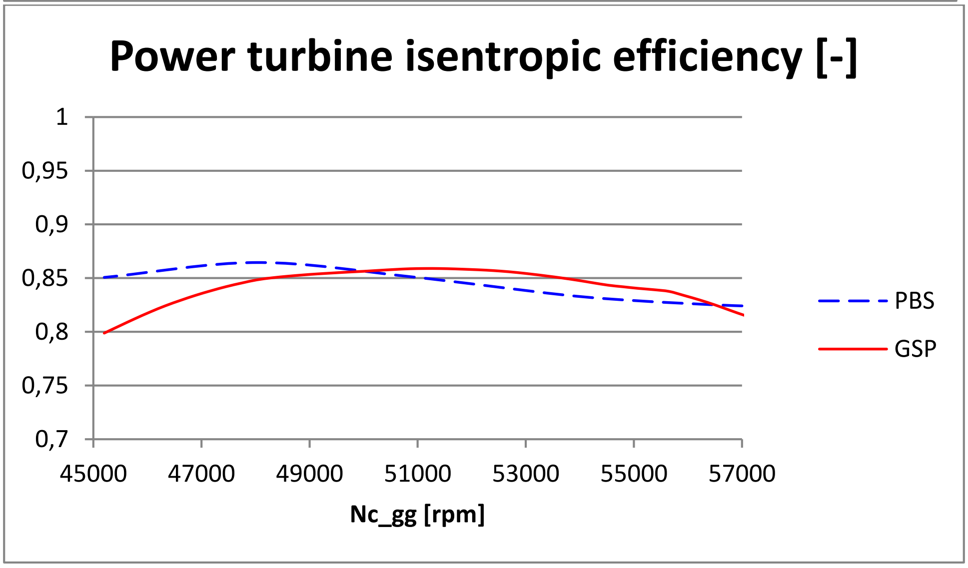

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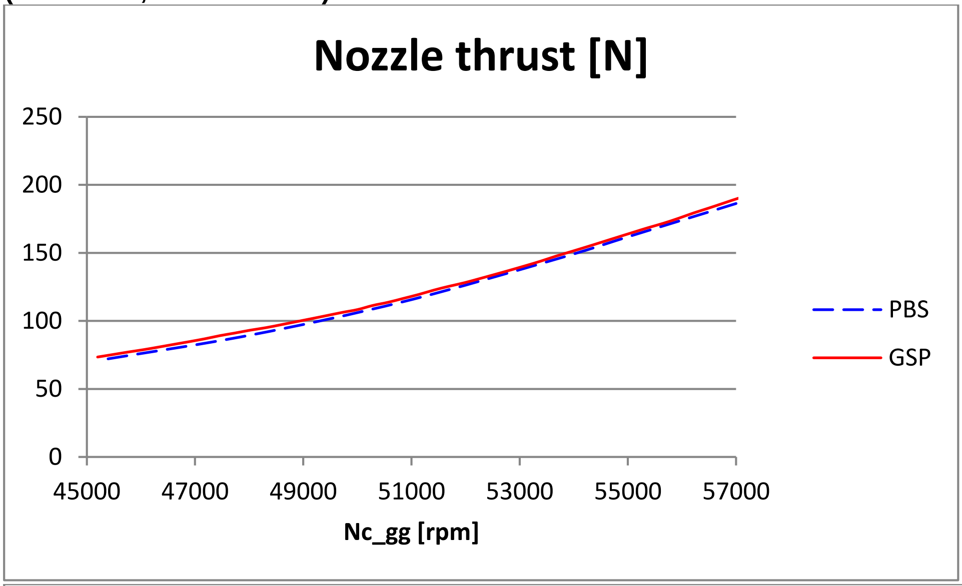

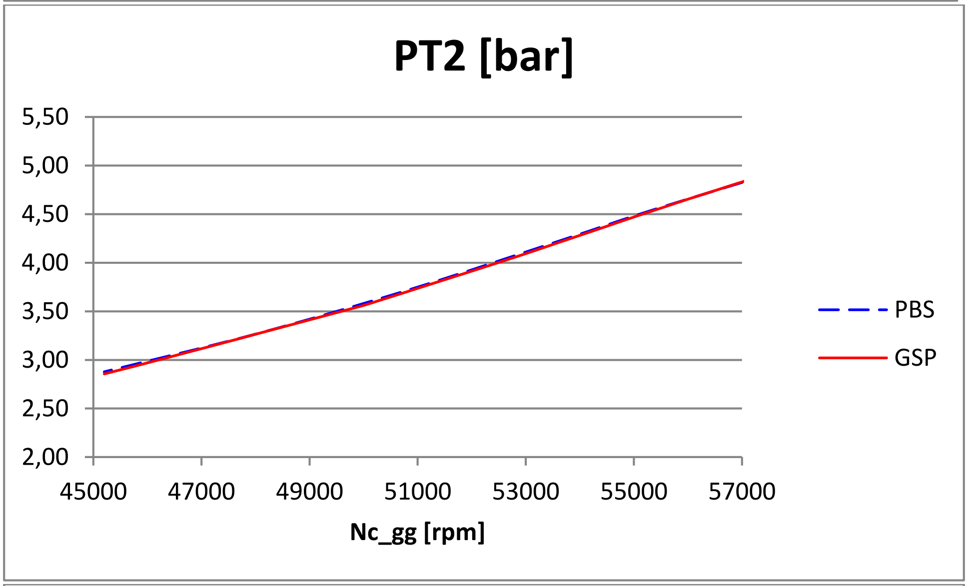

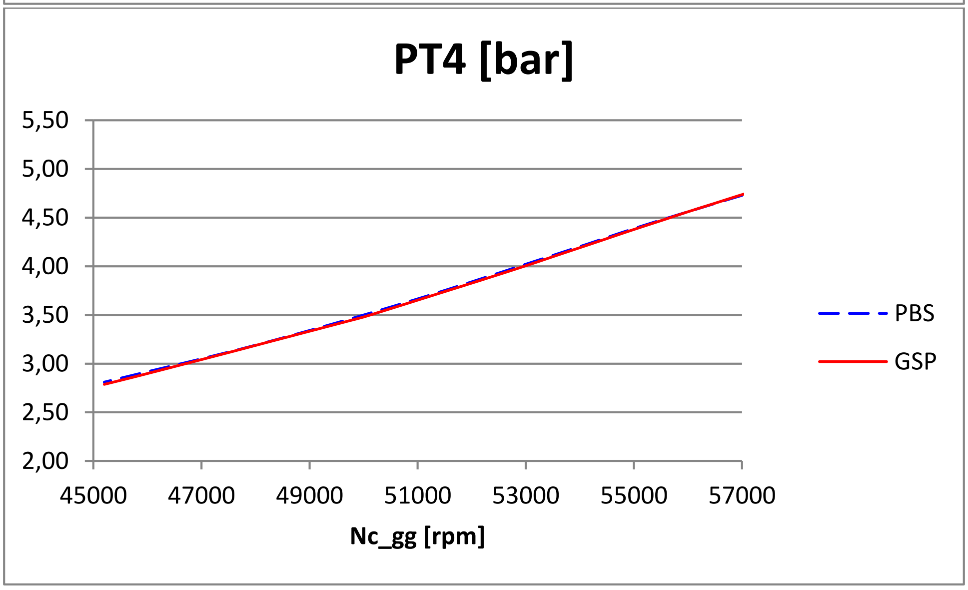

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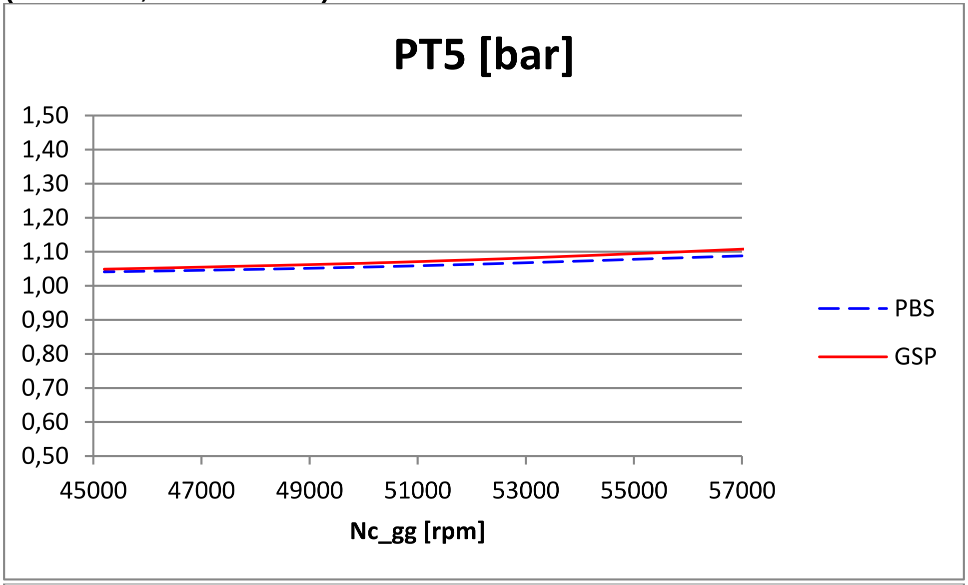

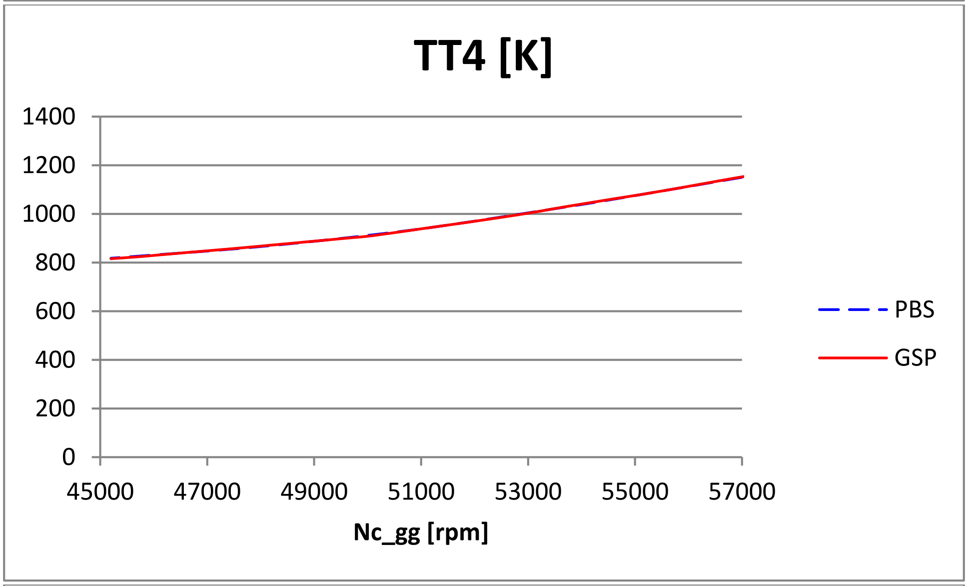

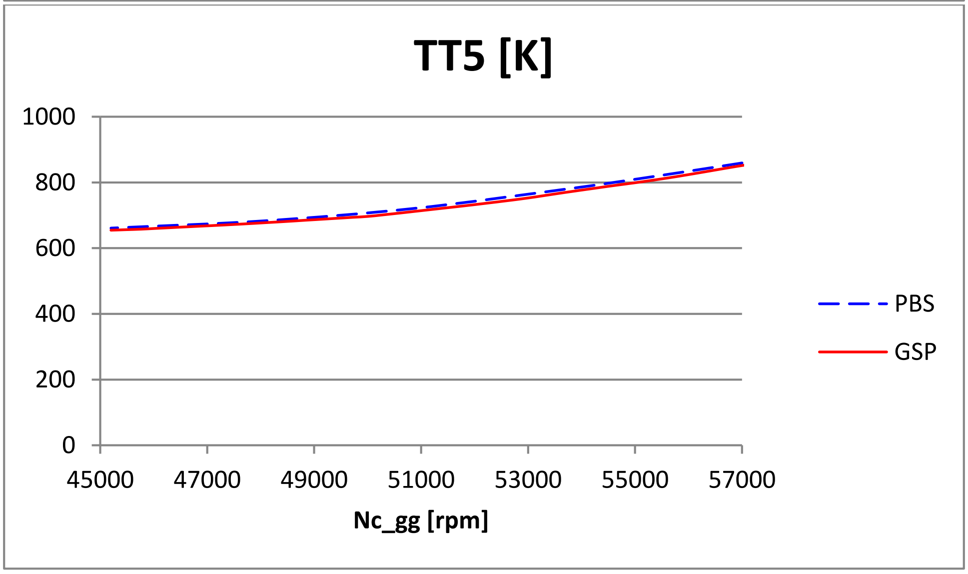

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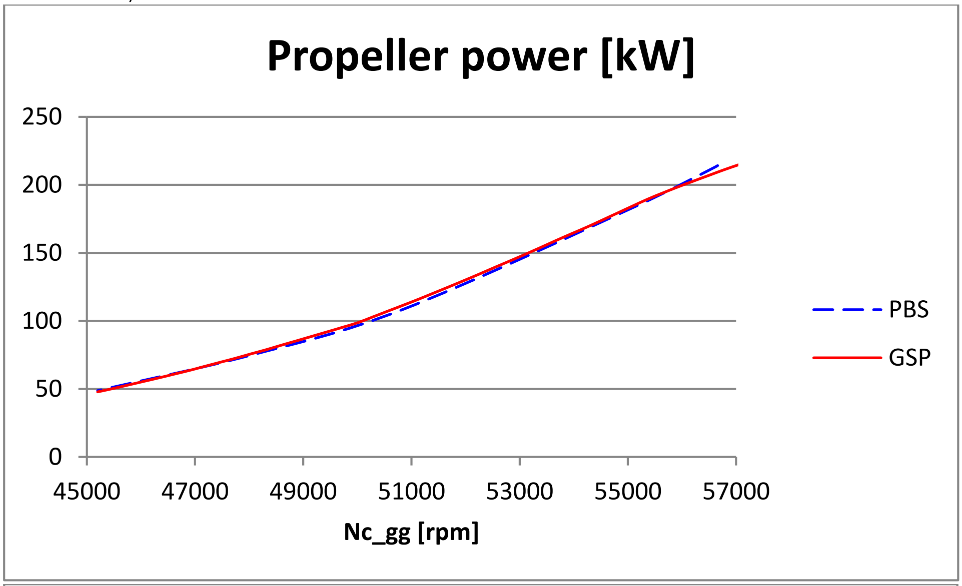

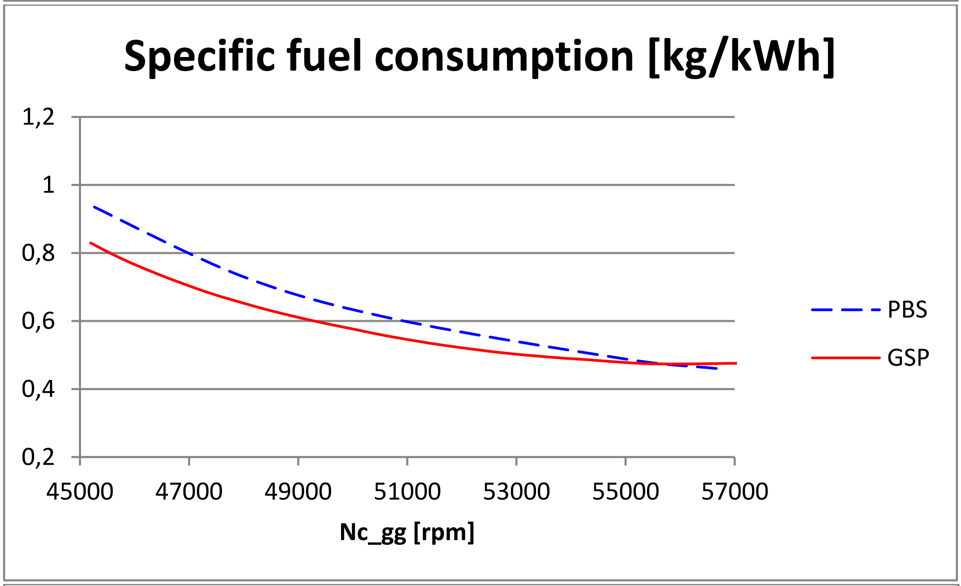

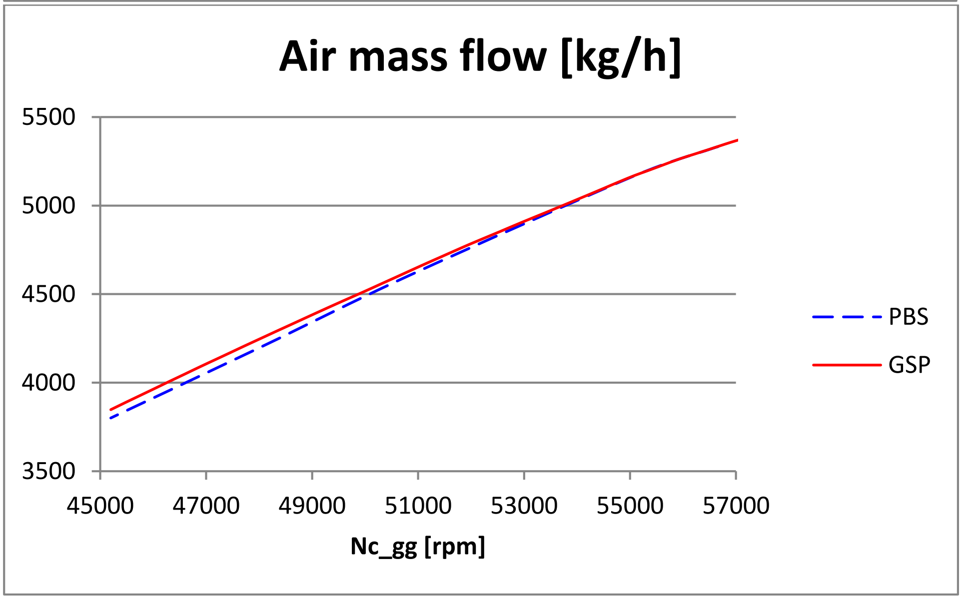

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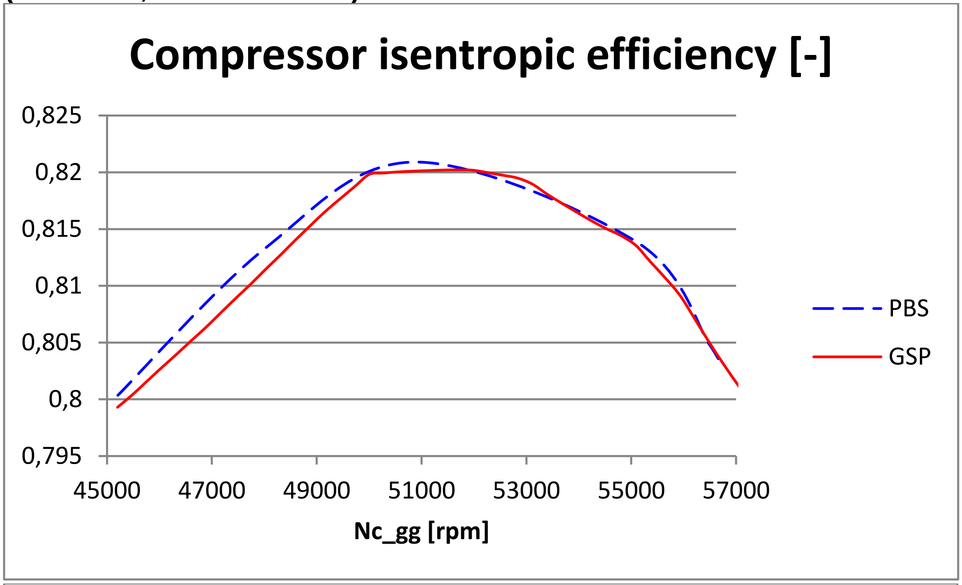

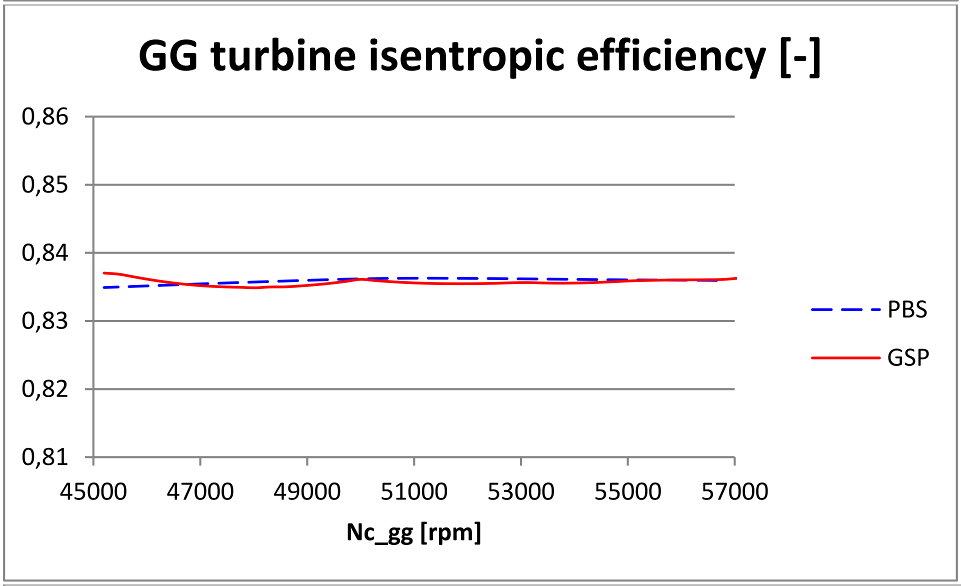

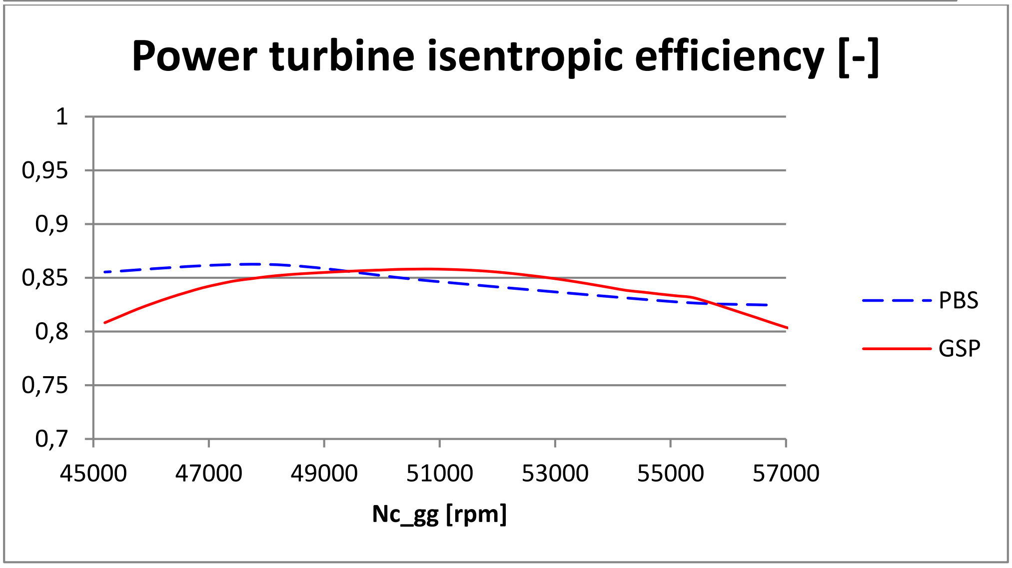

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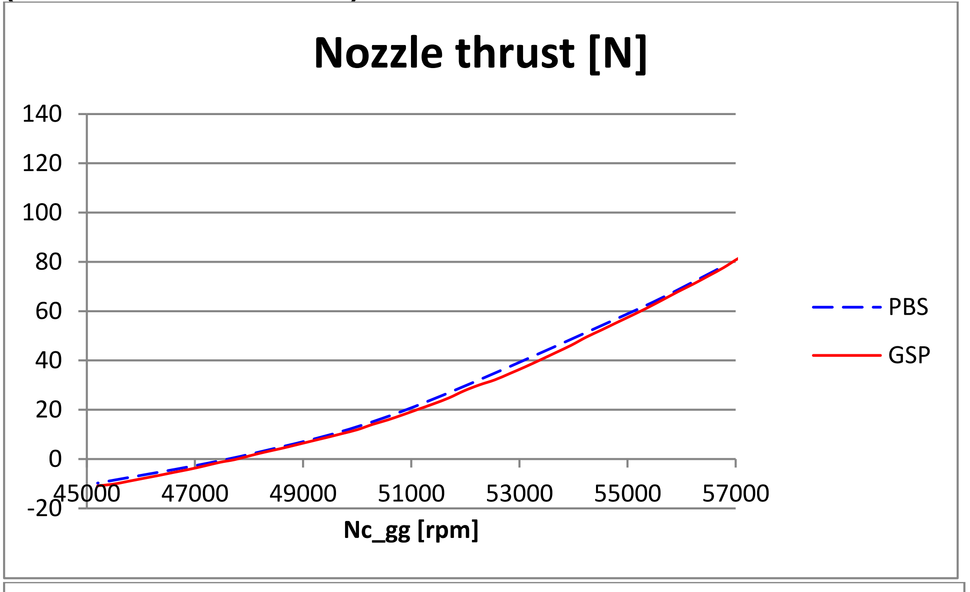

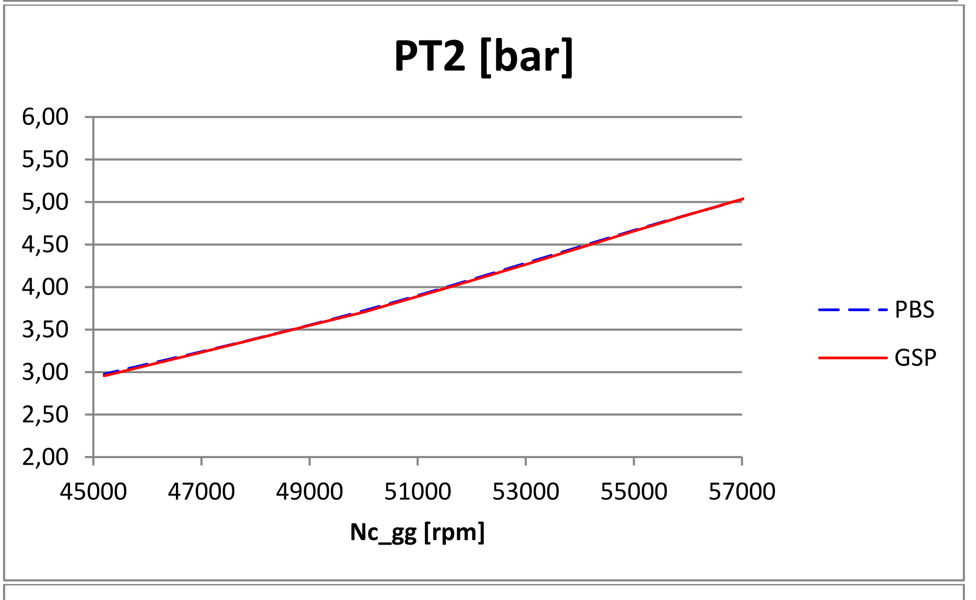

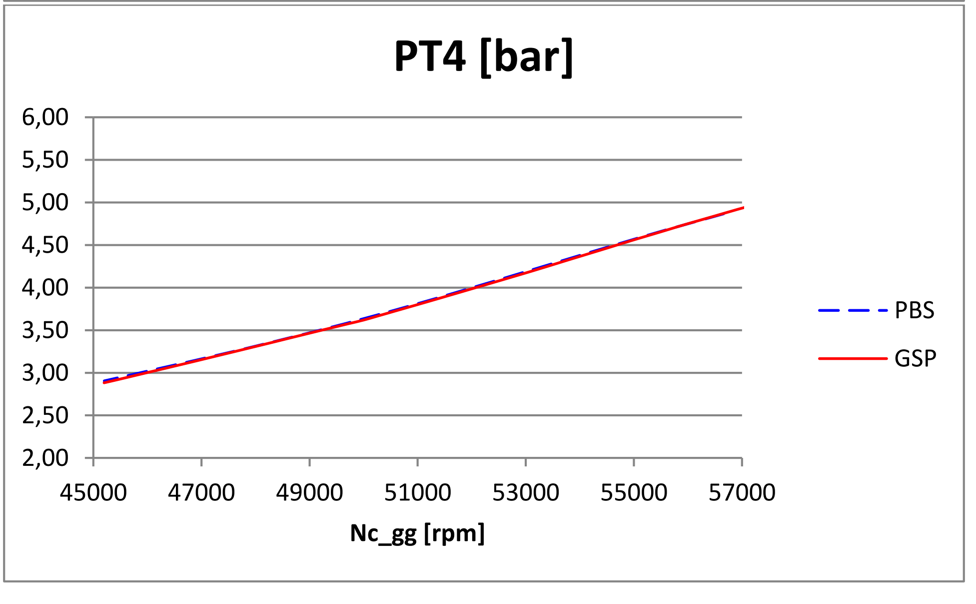

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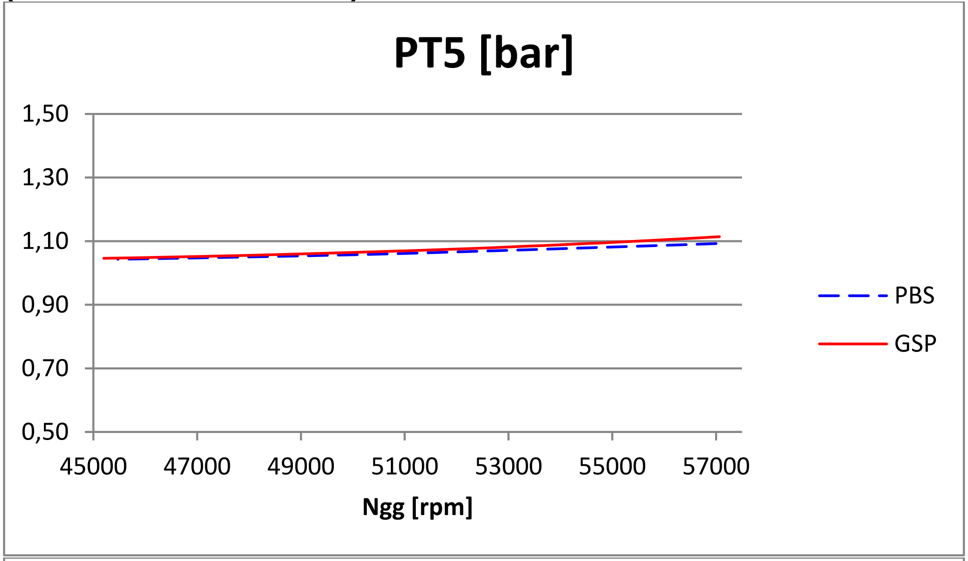

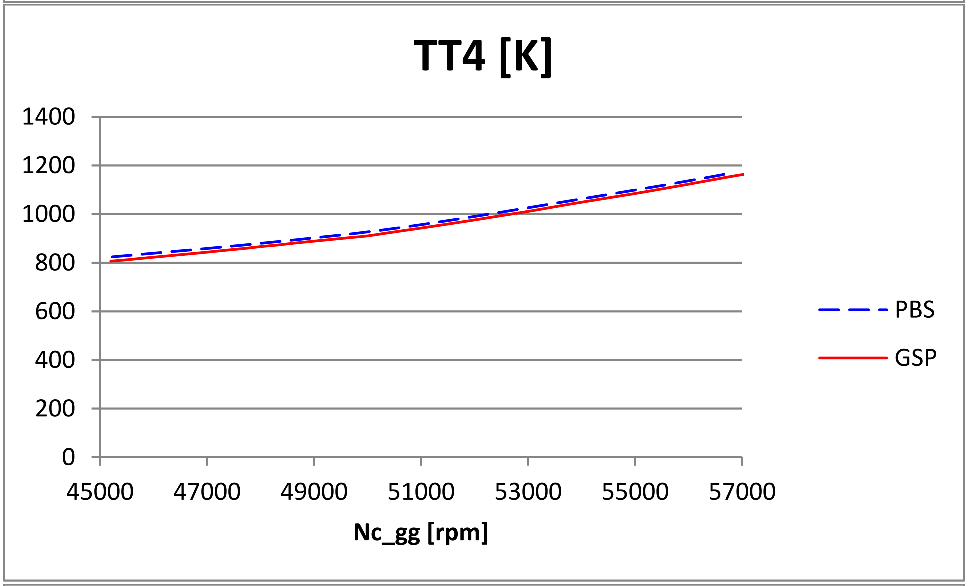

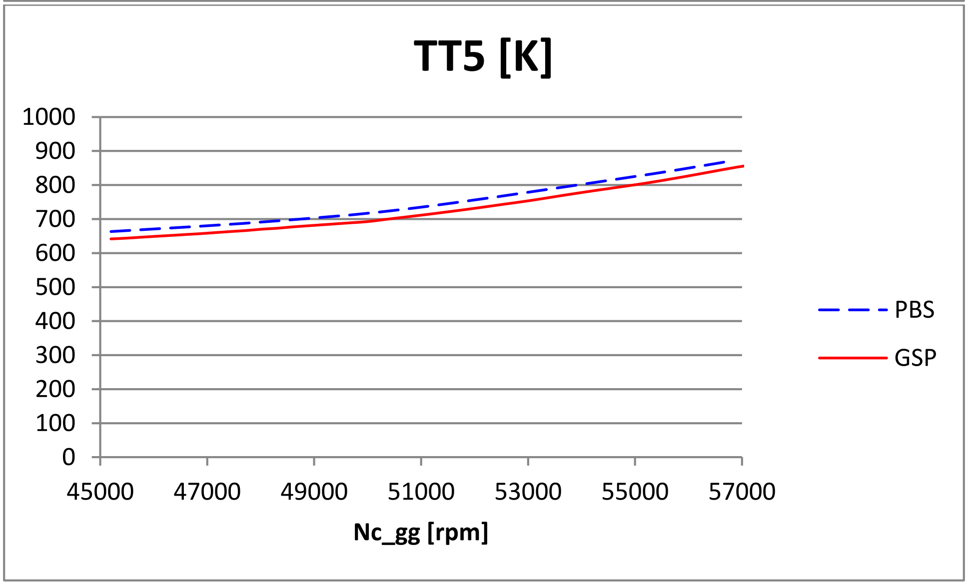

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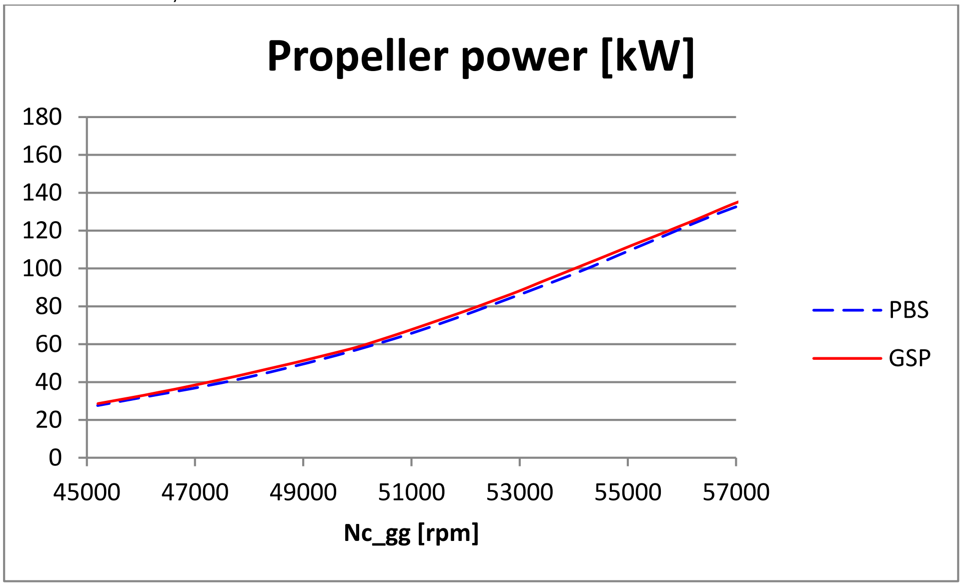

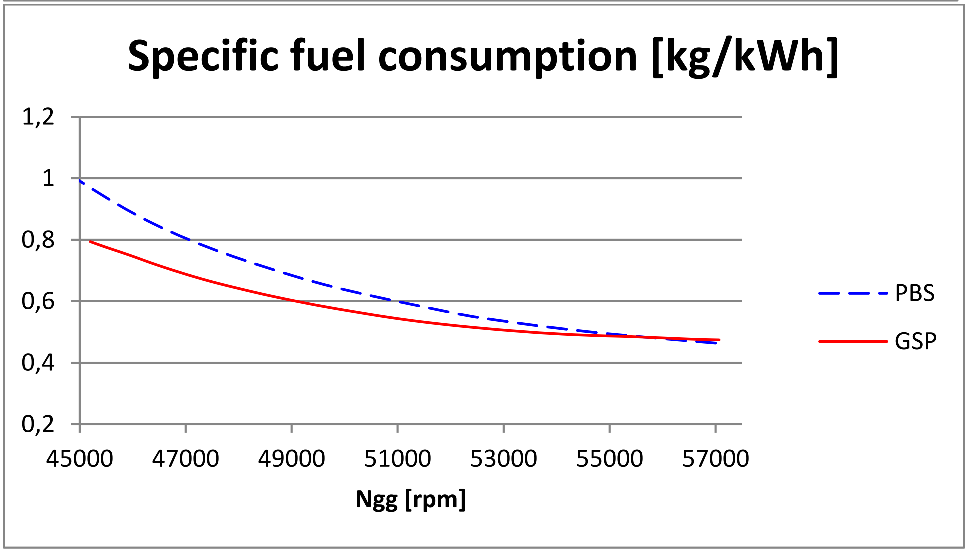

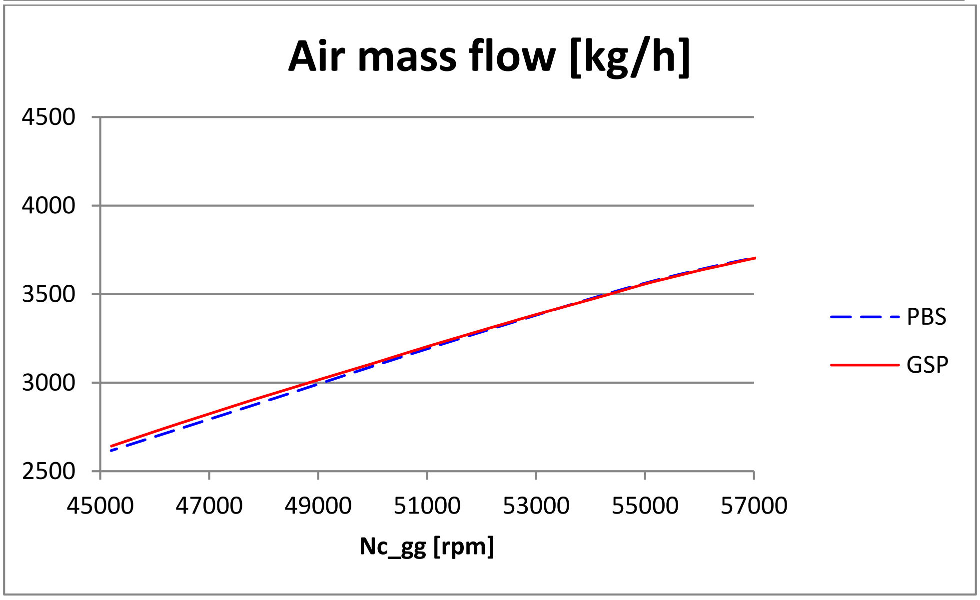

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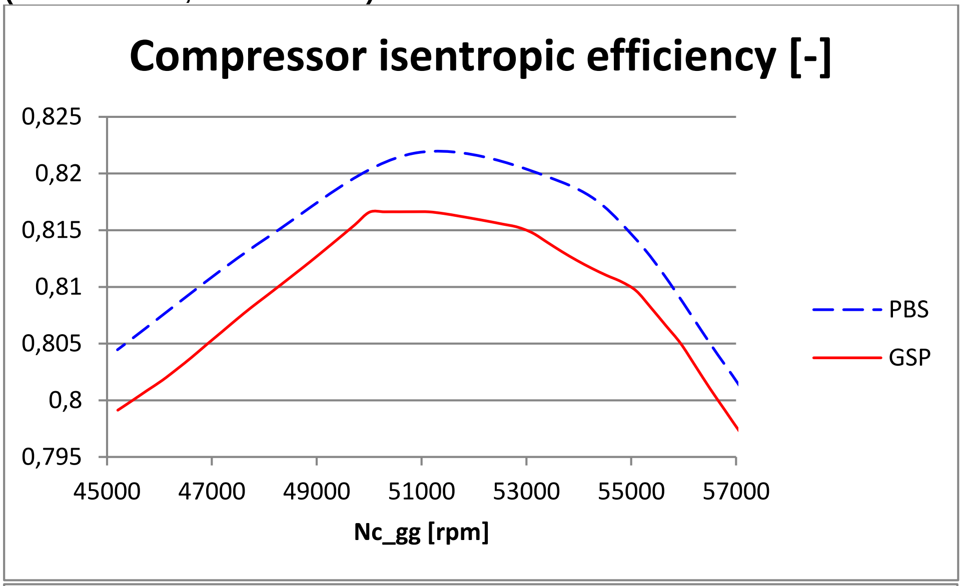

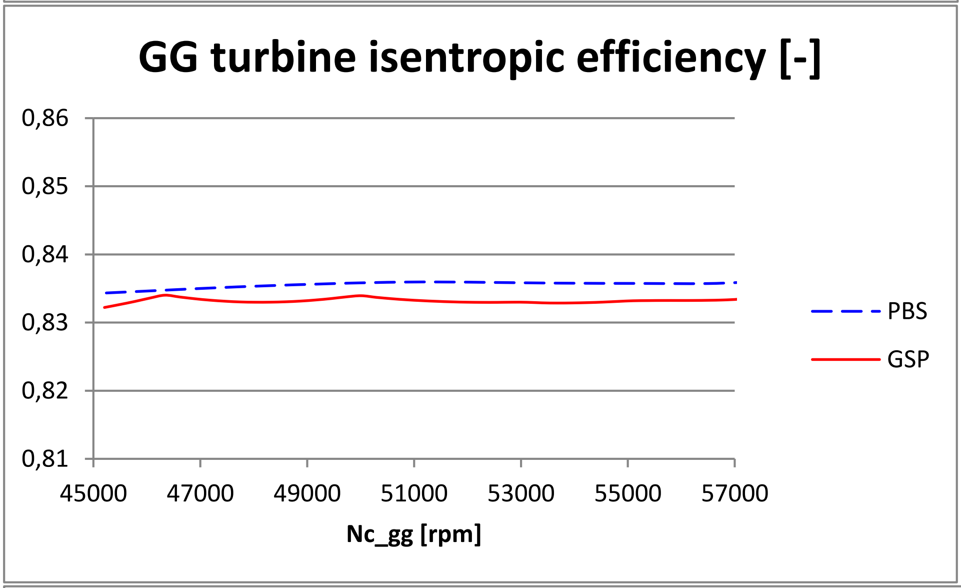

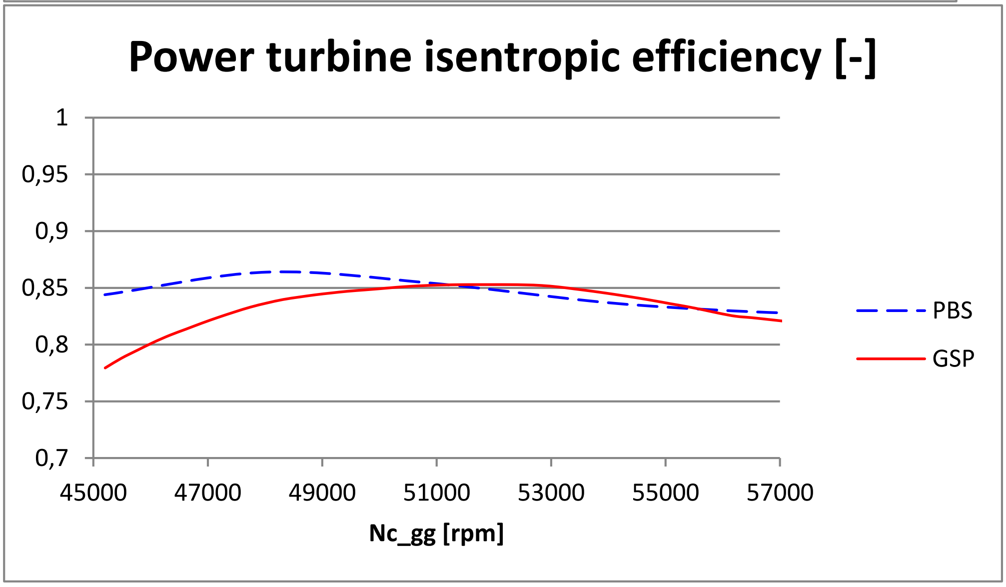

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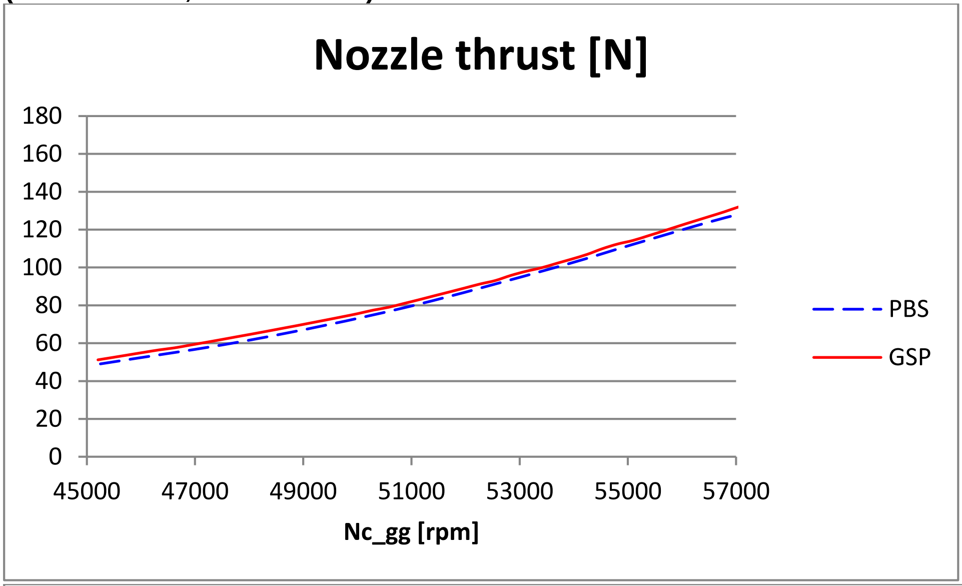

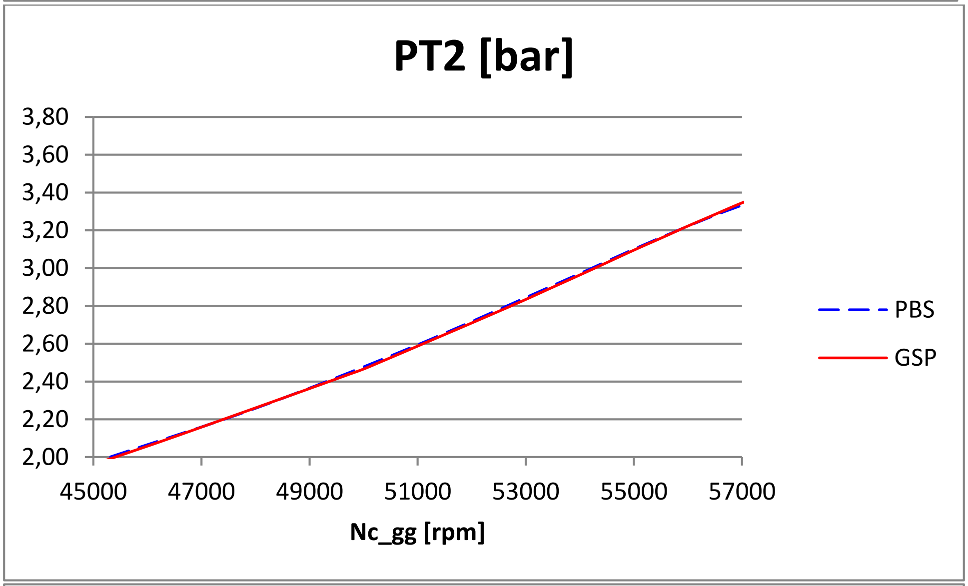

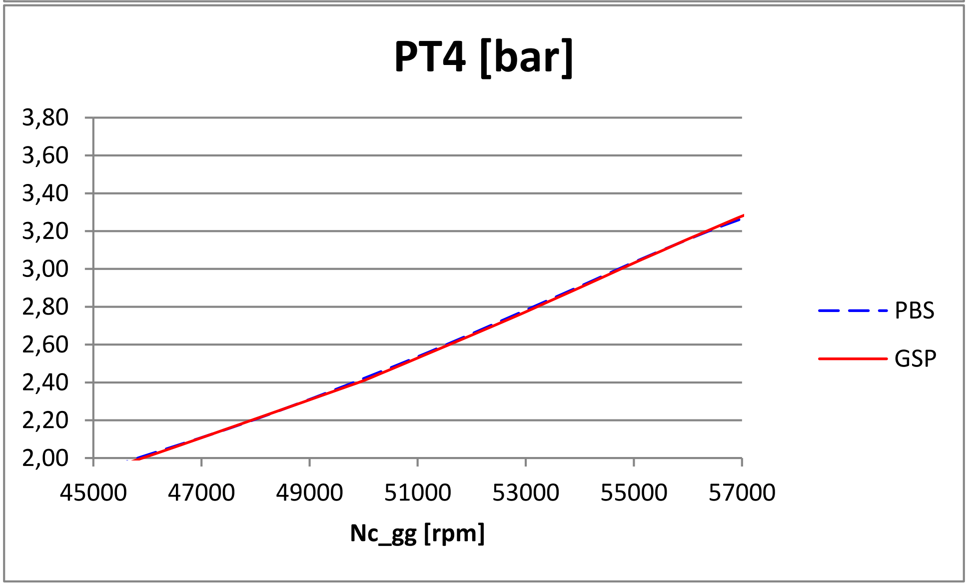

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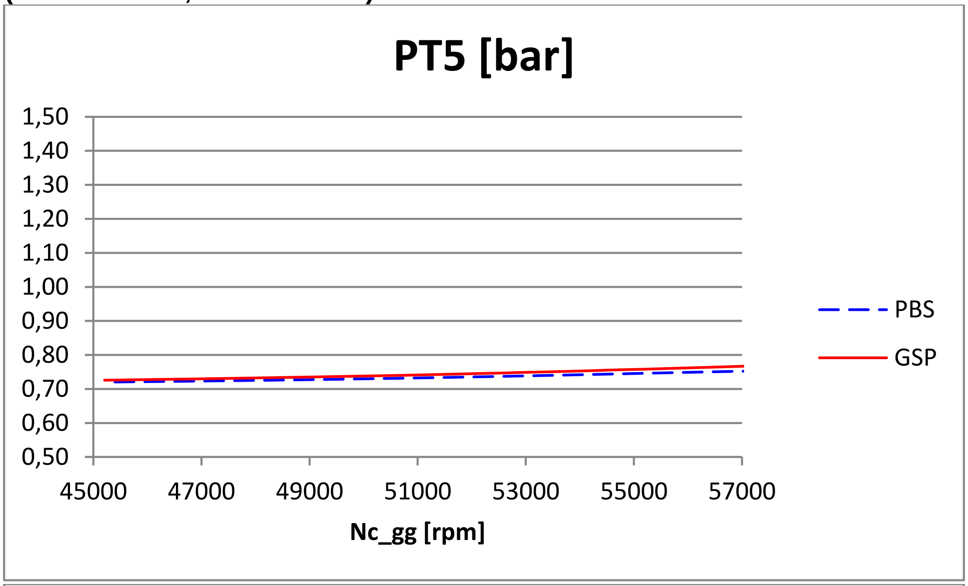

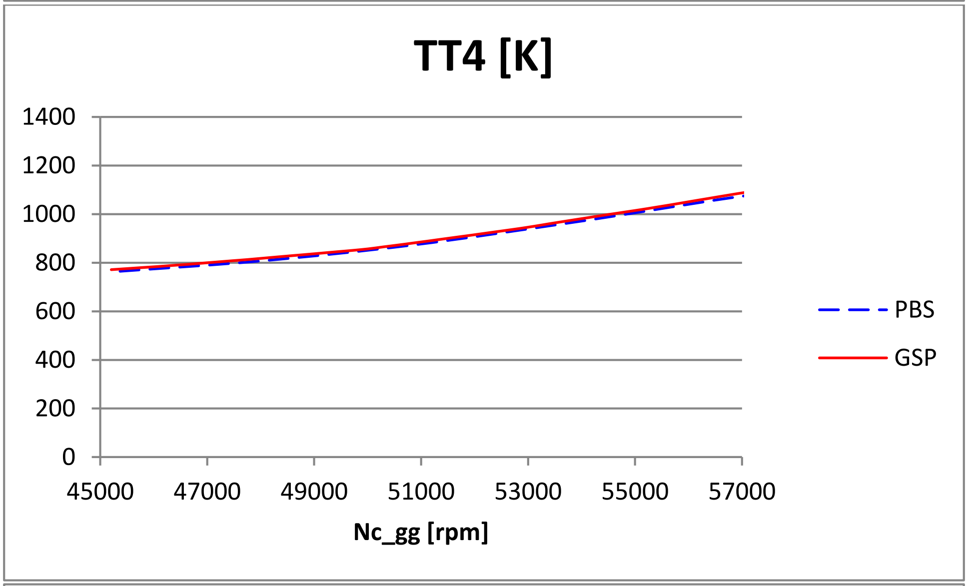

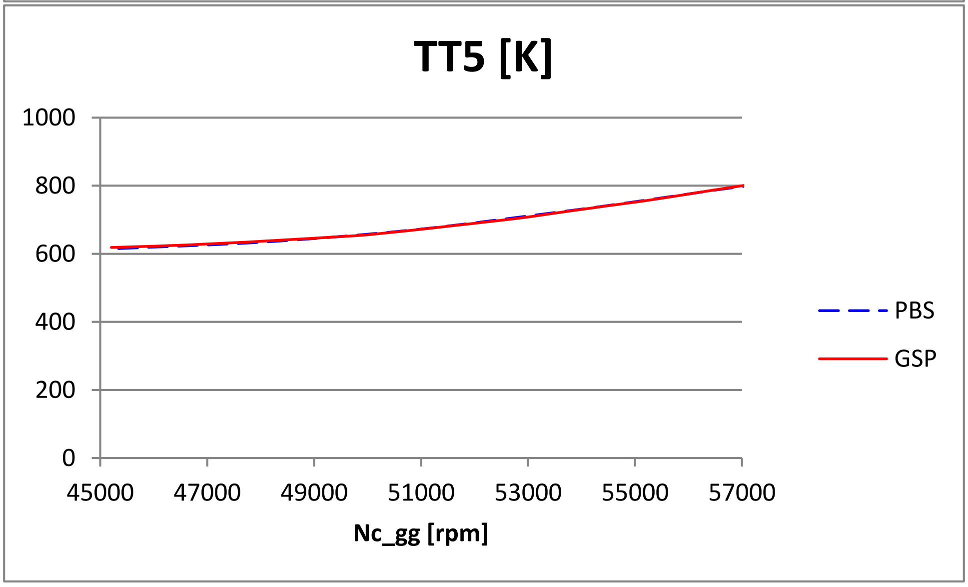

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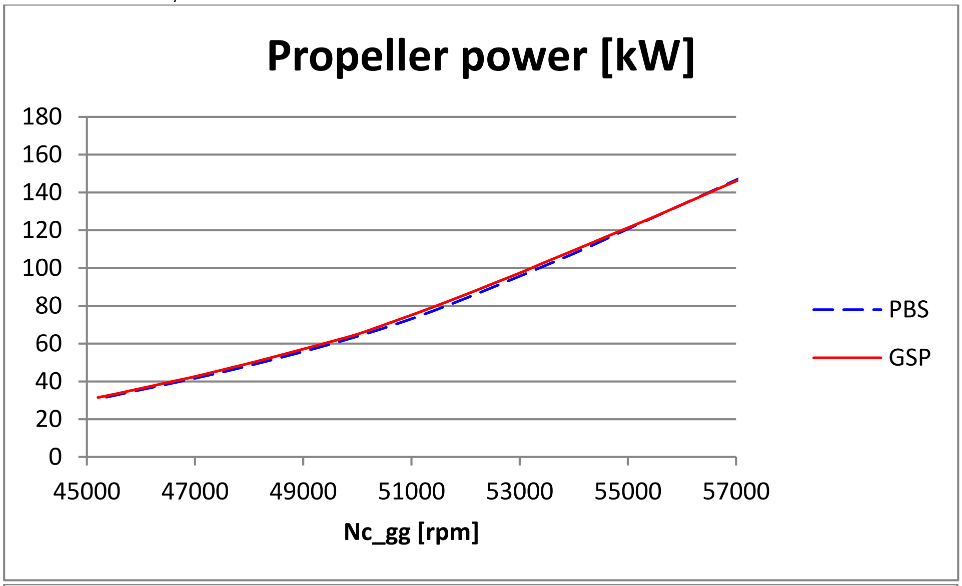

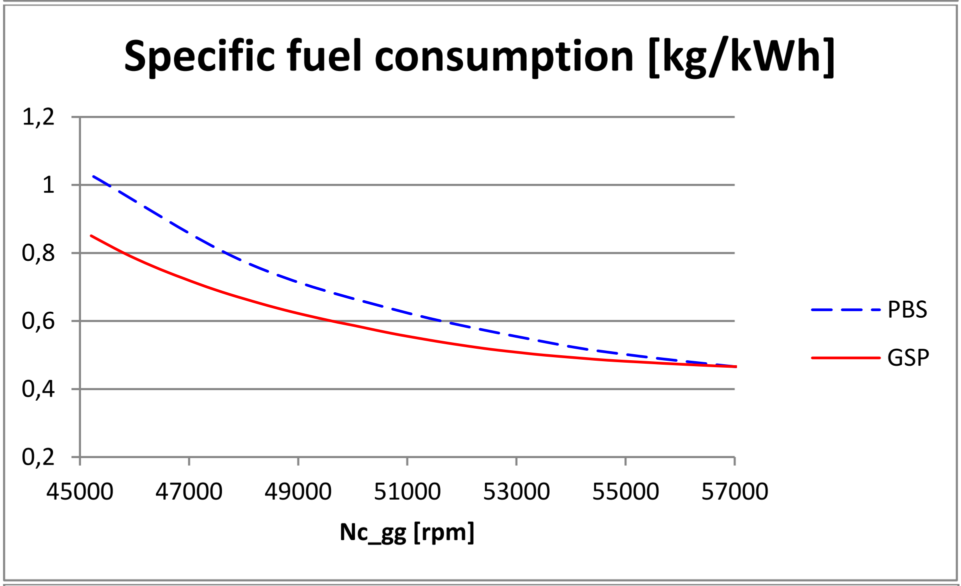

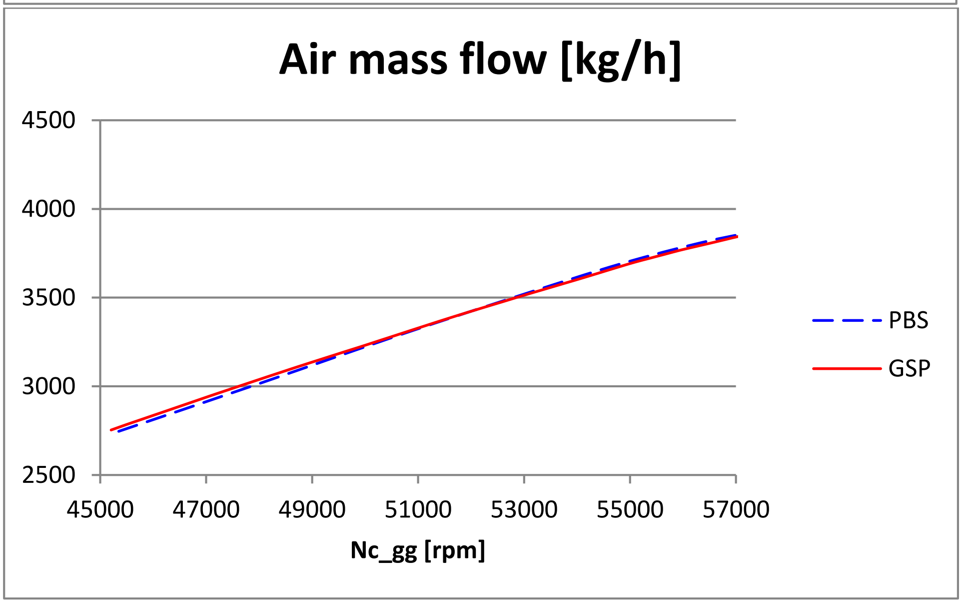

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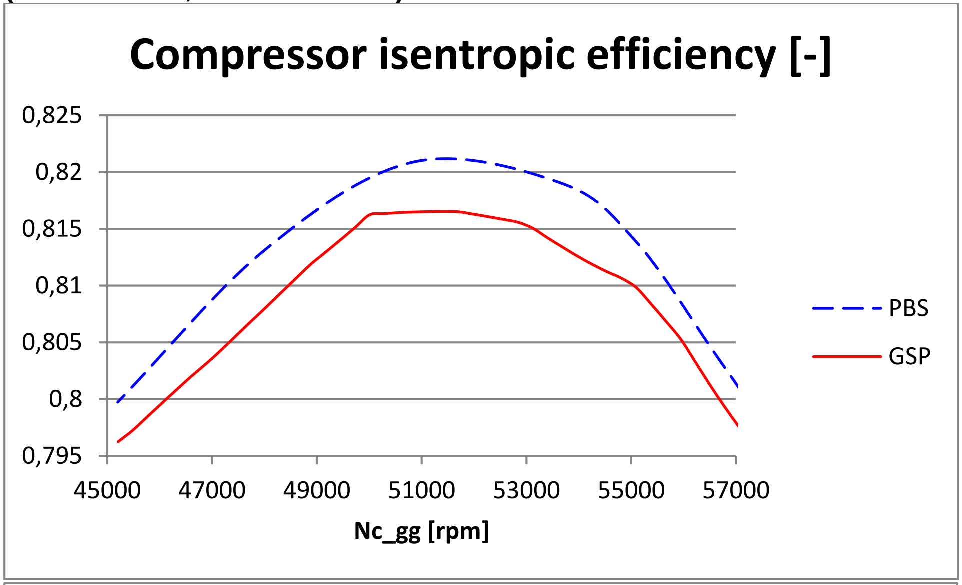

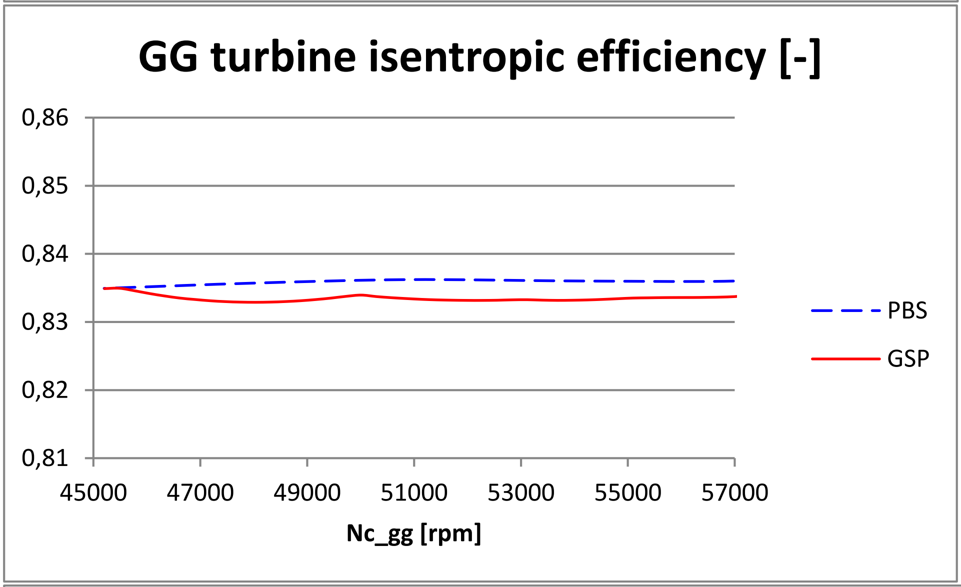

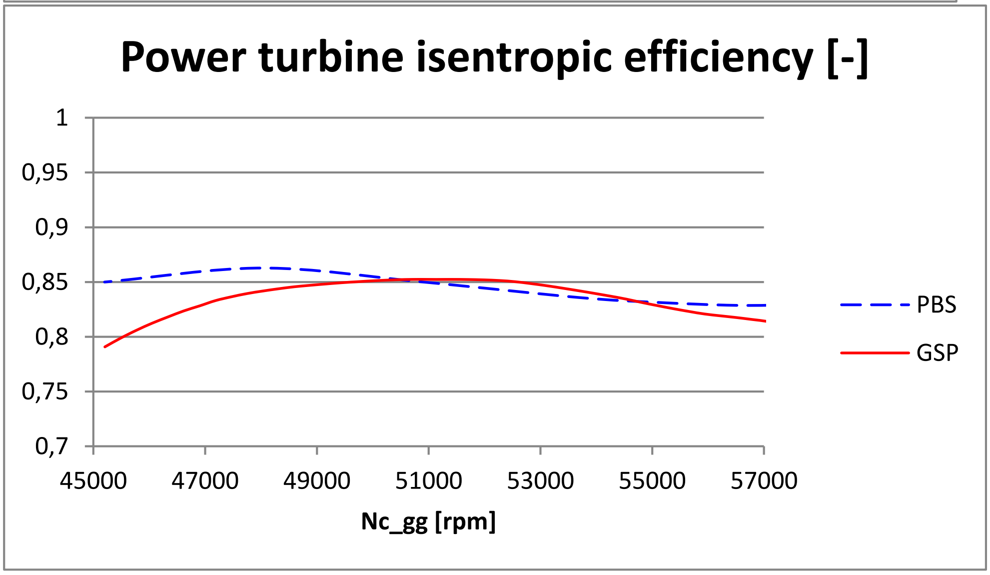

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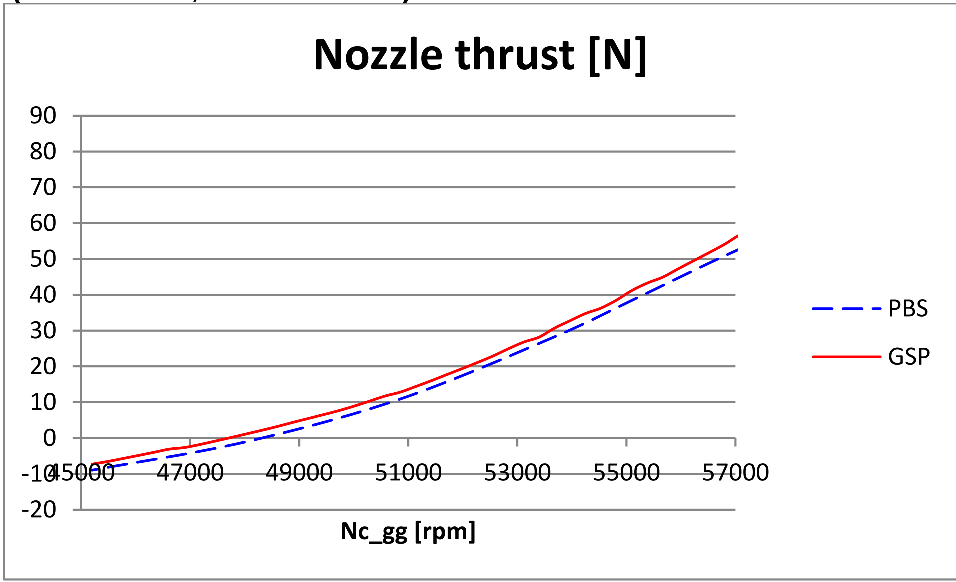

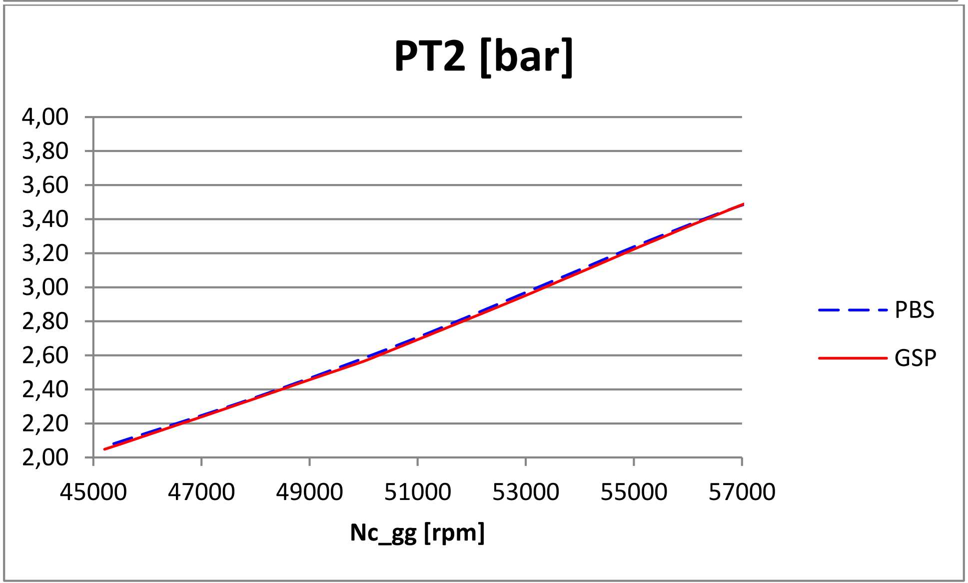

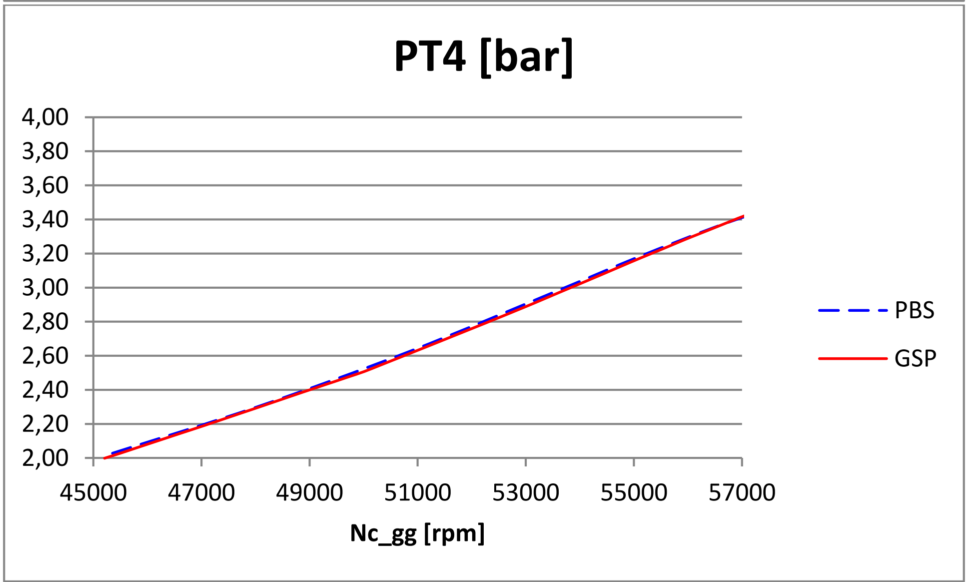

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