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Titel: GT-Power model Stork-Werkspoor 280

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1. Introduction
Wärtsilä Zwolle asked for a GT-Power engine model of their SW280 engine. GT-Power is a CAE (Computer Added Engineering) program, part of the GT-Suite engineering software. GT-Power is the engineering application in GT-Suite for internal combustion engine modelling, it could work with complex engine models from a single cylinder to a multi cylinder turbocharged engine.

The aim for this project; it is possible to build a complete computerised model simulating the 6 cylinder SW280. Describing the entire speed and load range to predict different motor parameters. An engine model in GT-Power is build using different smaller modules, like a cylinder module describing the combustion, or a turbine module with a turbine map. Every module has to be calibrated to input data of the existing engine. The engine model consist of a cylinder with combustion, fuel injection, inlet and exhaust system, charge air cooler and a turbocharger.
# 2. Index

1. Introduction .......................................................................................................................... 1
2. Index ...................................................................................................................................... 2
3. Summery.................................................................................................................................. 3
4. Wärtsilä .................................................................................................................................... 4
5. Project description .................................................................................................................. 4
6. Stork-Werkspoor 280 ........................................................................................................... 5
   6.1. Engine description ............................................................................................................. 5
   6.2. Test run .......................................................................................................................... 6
7. GT-Power ............................................................................................................................... 7
   7.1. Licenses .......................................................................................................................... 8
   7.2. Cases ................................................................................................................................ 8
   7.3. Design of experiment ...................................................................................................... 8
   7.4. Distributed calculations ................................................................................................. 10
   7.5. Combustions .................................................................................................................. 10
8. Approach .................................................................................................................................. 15
   8.1. Tutorials .......................................................................................................................... 15
   8.2. General numbers ............................................................................................................ 15
   8.3. Drawing .......................................................................................................................... 16
   8.4. Choose the right combustion simulation ........................................................................ 16
   8.5. Injection .......................................................................................................................... 17
   8.6. Valve timing and lift ....................................................................................................... 17
   8.7. Filter ................................................................................................................................ 18
   8.8. Accuracy ........................................................................................................................ 19
9. Building the full SW280 model .............................................................................................. 19
   9.1. Cylinder, crack shaft, valve and injection base .............................................................. 19
   9.2. Inlet and exhaust ............................................................................................................. 19
   9.3. Data input ....................................................................................................................... 20
   9.4. Environment .................................................................................................................... 22
   9.5. Combustion .................................................................................................................... 24
   9.7. Turbocharger ................................................................................................................... 26
10. Result ...................................................................................................................................... 28
   10.1. Burn rate / heat release ................................................................................................. 28
   10.2. Cylinder Pressure .......................................................................................................... 29
   10.3. Stoichiometric calculation ............................................................................................. 30
   10.4. Injection timing ............................................................................................................. 30
   10.5. GT-Power results against measured ‘Kenveld’ .............................................................. 31
11. Recommendations ............................................................................................................... 33
   11.1. Weaknesses in model .................................................................................................... 33
   11.2. Recommendations ......................................................................................................... 33
12. Source list .............................................................................................................................. 35
13. Conclusion ................................................................................................................................ 36
3. Summery
For tuning applications an engine performance model in GT-Power is requested by the service department of Wärtsilä Zwolle. An engine performance model in GT-Power consists of different smaller modules like a combustion, cylinder, engine cranktrain, intake and exhaust, charger cooler and a turbocharger. All these smaller modules got to be matched to existing data from the engine.

The main question is: how an engine performance model is build and how accurate that model will be. Before starting to build the model in GT-Power some tutorials and other practicing is done to fully understand how GT works. With that knowledge and experience the model is build from scratch. The model consists of combustion, 6 cylinders, crank train, intake and exhaust ports and valves, charge cooler and a turbocharger.

The results are without the turbocharger because the turbine map was not accurate enough. The results that have been achieved are been satisfactory. A fully predictive combustion through the entire speed and load range. Accurate results for temperatures and pressures airflow through the engine and a fine working compressor map. The recommendations for this project further are to complete the turbine map and used the newest predictive combustion model that has been released by GT-Power.
4. Wärtsilä

The Finnish company Wärtsilä has offices around the world. It employs approximately 17,500 employees. Wärtsilä is active in various sectors where large engines do the job. Wärtsilä provides complete power plants and propulsion systems for ships. It produces the 2- and 4-stroke engines and propulsors. The development of 4-stroke engines takes place in Finland and Italy, the 2-stroke development take place in Swiss and the development of propulsors takes place in the Netherlands.

The Dutch branch of Wärtsilä consists of six branches with approximately 1,500 employees. A part of Wärtsilä Netherlands is the service department; responsible for the technology. It is located in Zwolle and has been divided into different departments with their own expertise. The department where the graduation takes place is the Expert Service department.

Wärtsilä Netherlands have relatively new engines but also older engines from Dutch designs like Kromhout, Stork, Werkspoor and Bolnes. In 2005, Wärtsilä Netherlands adopted marine Deutz In 2010, Sulzer constructing 4-stroke engines have been added. The service department of Wärtsilä Netherlands, provided services for 19,000 engines from 40 different engine types.

As so-called 'non portfolio' Wärtsilä Netherlands firm has a special position within the Wärtsilä group and is technically the owner of the above products. Besides the service activity is therefore in Zwolle providing development to the existing installation to maintain.

5. Project description

The SW280 engine is a heavy duty turbocharged diesel engine; it is expensive and inconvenient to test any performance modifications. Therefore it is attractive to have an engine performance model (computer simulation) of the engine. This performance model is based on GT-Power, an engineering application in GT-Suite and has been calibrated by using actual data as derived from an extensive test program.

The performance model must be build from scratch including a cylinder containing a combustion, fuel injection, intake and exhaust system, air cooler and a turbocharger.

This project starts with a lot of reading and experimenting in GT-Power because this piece of equipment was unknown. The approach for this project will be described in chapter 5 Approach. With the experience and knowledge collected during the first part of the project the engine model has been built.
6. Stork-Werkspoor 280
This section contains a description of the engine that has to be simulated by the GT-Power model. What does the engine look like and what for dividend parts are mounted on it. Further it describes what for measurements are be done in the past.

6.1. Engine description
In the seventies of the last century 'Stork-Werkspoor' has designed, developed and constructed an engine in the Stork-Werkspoor 280 series (SW280). The SW280 "heavy duty" diesel engine is a four stroke, medium speed engine. The 280 engine has been designed for continuous use under severe operating conditions. The SW280 is the result of experiences obtained from earlier built diesel engines. The SW280 has several models. These can be either running clockwise or counter-clockwise. There are 6, 8 and 9 cylinder engines in line and 12, 16 and 18 cylinder V-engines. The engine can be used for power generation (electricity) and in marine propulsion.

6.1.1. Engine
As already indicated above the SW280 is available in different versions: 6, 8, 9 cylinders in line and V12, V16 and V18 cylinder. The Engine block and camshaft are made out one-piece. E.g. the total weight of the engine block and the camshaft of the V16 version is more than 34,000 kg. The camshaft has hydraulic shrink fitted cams. This allows the cam to be re-adjusted when necessary.

The triple deck cylinder head has two inlet and two exhaust valves. The engine starts with compressed air, therefore the cylinder head also contains a starting air valve.

6.1.2. Fuel, oil and water system
The fuel system consist of a fuel feed pump for ‘marine diesel oil’ (MDO) only, a duplex fuel filter, high-pressure fuel pumps and a fuel injector. Each cylinder has a dedicated high-pressure fuel pump. The system is further provided with one or two engine driven lubricating oil pumps, oil cooler, a change-over duplex filter and a centrifugal filter. The cooling water system comprises a low-temperature (LT) circuit and a high-temperature (HT) circuit. The LT-circuit includes the second stage charge air cooler and lubricating oil cooler. The HT circuit includes the cylinders and turbocharger and the HT-stage of the charge air cooler.

6.1.3. Exhaust and turbocharging
The exhaust pipes are heat insulated and have one or two turbochargers on it. The turbochargers are arranged at the flywheel ends. The air is charge cooled by the LT-circuit.
6.1.4. Performance

For the SW280 series, several sets of measurements are available. The table below contains the most important characteristics of the several SW280 types.

### TECHNICAL DATA

<table>
<thead>
<tr>
<th>Engine type</th>
<th>6SW280</th>
<th>8SW280</th>
<th>9SW280</th>
<th>12SW280</th>
<th>16SW280</th>
<th>18SW280</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>in-line</td>
<td>in-line</td>
<td>in-line</td>
<td>50 V</td>
<td>50 V</td>
<td>50 V</td>
</tr>
<tr>
<td>Number of cylinders</td>
<td>6</td>
<td>8</td>
<td>9</td>
<td>12</td>
<td>16</td>
<td>18</td>
</tr>
<tr>
<td>Bore/stroke</td>
<td>mm</td>
<td>280/300</td>
<td>280/300</td>
<td>280/300</td>
<td>280/300</td>
<td>280/300</td>
</tr>
<tr>
<td>Displacement</td>
<td>l</td>
<td>110,82</td>
<td>147,76</td>
<td>166,3</td>
<td>221,64</td>
<td>95,52</td>
</tr>
<tr>
<td>Compression ratio</td>
<td></td>
<td>13</td>
<td>13</td>
<td>13</td>
<td>13</td>
<td>13</td>
</tr>
<tr>
<td>Direction of rotation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Clockwise or counter-clockwise

#### Maximum power ratings

<table>
<thead>
<tr>
<th>Engine speed</th>
<th>kW</th>
<th>720 - 1000</th>
<th>720 - 1000</th>
<th>720 - 1000</th>
<th>720 - 1000</th>
<th>720 - 1000</th>
<th>720 - 1000</th>
<th>720 - 1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine output</td>
<td>kW</td>
<td>1560 - 1800</td>
<td>2080 - 2400</td>
<td>2340 - 2700</td>
<td>3120 - 3600</td>
<td>4160 - 4800</td>
<td>4680 - 5400</td>
<td>4680 - 5400</td>
</tr>
<tr>
<td>Mean effective pressure</td>
<td>bar</td>
<td>19.5 - 23.4</td>
<td>19.5 - 23.4</td>
<td>19.5 - 23.4</td>
<td>19.5 - 23.4</td>
<td>19.5 - 23.4</td>
<td>19.5 - 23.4</td>
<td></td>
</tr>
</tbody>
</table>

#### Table 1 SW280 Technical data

### 6.2. Test run

The SW280 6 cylinder has been tested intensively: 32 test runs have been carried by varying speed from 400 to 1000 RPM and a ‘Brake Mean Effective Pressure’ (BMEP) from 1 to 21 bar.

However, the test run carried out at 400 rpm and 1 bar BMEP cannot be used: During that test run the engine showed instabilities. So 31 tests are available for calibration.

All the main output points are divided into several subpoints. A full list can be found in the appendix 1 Kenveld measurement.

The main test points are given below in table 2 Measurements ‘Kenveld’:

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Load</td>
<td>• Fuel</td>
</tr>
<tr>
<td>• Power</td>
<td>• Environment</td>
</tr>
<tr>
<td>• Engine speed</td>
<td>• General info</td>
</tr>
<tr>
<td>• Mean effective pressure</td>
<td>• Combustion</td>
</tr>
<tr>
<td>• Rack</td>
<td>• Turbocharged</td>
</tr>
<tr>
<td></td>
<td>• Cylinder cooling</td>
</tr>
<tr>
<td></td>
<td>• Cooling water pressure group feel</td>
</tr>
<tr>
<td></td>
<td>• Air coolers and heaters</td>
</tr>
<tr>
<td></td>
<td>• Injector cooling</td>
</tr>
<tr>
<td></td>
<td>• Lubricating oil</td>
</tr>
<tr>
<td></td>
<td>• Fuel</td>
</tr>
<tr>
<td></td>
<td>• Cylinder-related parameters</td>
</tr>
<tr>
<td></td>
<td>• Emission</td>
</tr>
</tbody>
</table>

Table 2 Measurements ’kenveld’
7. GT-Power

GT-Suite is a CAE program that has been designed for the automotive branch and exists of different engineering applications. For this project the main focus is concentrated on the GT-Power application for internal combustion engine modelling. A GT-Suite application has been built using smaller modules and a Java script based environment. The user interface has a Matlab/Simulink appearance. Each module contains dedicated calculation templates for different parts of the internal combustion engine such as a cylinder, an injector, a cranktrain, in- and exhaust valves, turbochargers and piping for intake and exhaust. All these parts can be opened by clicking on it, and defined in Flow, mechanical, control or thermal. Actually it is a chain of blocks all having their own formulas and passing answers/results to the next block.

Figure 1, example of GT-Power
7.1. Licenses

GT-Suite works with a license server to use different parts of the program. These licenses can be driven on an USB drive or an external server. Wärtsilä has got an external license server with 12 licenses to use the GT-Ise part for building and viewing applications and 12 licenses for the GT-Suite for calculations on applications. These licenses are ‘floating licenses’ and can be used by all Wärtsilä employees.

The development departments are the most important and frequent users; for the service department GT-Suite is a significant new (relatively unknown) piece of equipment. The 12 licenses for the GT-Ise and GT-Suite have to be divided between these departments but users in the developments departments have a higher priority than users in the service departments.

7.2. Cases

GT-Power uses cases to define different situations. For each case different parameters has to be set for calculations. In the case setup all cases can be defined and described with all desired parameters. Names of parameters to be used have to correspond with the names listed. For example [rpm], the 'engine speed' in the case setup.

7.3. Design of experiment

For complex systems with several parameters it is not always possible to predict what will happen. In some cases, GT-Power is not capable to do the desired predictions. For those cases, a program, called Design of Experiment (DOE) available. It has been developed by GT-Power as well. It allows the model to calculate it many times and with the results to find an optimum. The principles of GT-DOE are explained in the following paragraphs.

7.3.1. DOE-Setup

There are six DOE types available: a full factorial design, three partial factorial designs, a screening experiment design and a user option. All the different approaches will be explained in the appendix 2 ‘DOE-setup’. Partial factorial designs can be used to determine the relationships between the dependent (response) and independent (factor) variables while running fewer experiments than would be required for a full factorial design. A screening experiment is designed to determine qualitatively which factors have a significant effect on the response by looking mainly at the first order linear response. In this way a relatively small number of experiments are required to determine the significance of a factor to a response. This is often used as a first screening to determine whether factors will be included in further full or partial factorial experiments to investigate the same response.
7.3.2. DOE-Run

Each experiment results in a case. Converting an experiment into a case can be very time consuming. However, the calculation time can be reduced significantly by using more, parallel operated, computers. But still, the results are complicated and difficult to handle. To use this data to work with it, GT-Power has created a tool named DOE-Post.

7.3.3. DOE-Post

A DOE-setup that has been calculated in GT-Power can be opened with DOE-Post to view the calculated values. However, large DOE-setups cannot be opened with the normal GT-post viewing tool because of too much information (data and/or graphs). The DOE-post viewing tool does not show all the details of the results, but only the most important. Further, the DOE-post tool combines all the calculations and will plot overall results in graphs.

One special application in the DOE-post is the optimizer. The main function is to find an optimum in a large set of results. To find an optimum a reference value and calculated value has to be selected and the smallest difference is found as an optimum.

![Figure 3](image)

**Figure 3, Example of a possible GT-Post 3D graph result**

Both graphs contain the following:
- X-axis: DJet-cair, ‘multiplier after combustion’
- Y-Axis: DJet-cbair, ‘multiplier before combustion’
- The x and y results in:
- Z-axis: parmserrbr, ‘RMS Error (predicted vs. Measured Burn Rate)’

Figure 3A, clearly shows an optimum in the dark red part of the curve. On the other figure 3B, does not have that optimum. Does optimum is out of it range.

For computer simulations by iteration it is essential that an optimum can be found. (‘Converging’ of the model). In many cases a simulation stops after a predefined number of iterations with the message: ‘not converged’.
7.4. Distributed calculations

The calculation time is rapidly increasing with the increasing amount of steps in the model; either flow, mechanical or combustions steps. And by multiplying these steps with a large amount of cases in a Design of Experiments (DOE) setup the calculation time on a single core can be hours. To reduce this cluster of comparable calculations has been made for ‘distributed calculations’ and distributed over several cores and computers. However it is limited by the fact that for each core is one license required, that Wärtsilä only has 12 licenses and the employees of the development department have got a higher priority to use these licenses.

![Distributed Network Diagram](image)

**Figure 4, distributed network**

The main advantage is to reduce calculation time, for example a quite big DOE-setup would take 134 hours on a single core but with the distributed network with 5 cores it was only 42 hours. A distributed network with 2 cores is not twice as fast as a single core calculation. This is caused by the fact that the distributor server uses one core to divide the cases and send them to different solvers. And after the calculation procedure all results have to be merged into one final result.

1 GT-Suite Distributed Computing and Remote Run

7.5. Combustions

Description of the combustion is the most important part of a complete engine model, every module has got a reference to the combustion. The combustion is described as a burn rate (the amount of fuel that is burned, which is not the same as the heat release). There are different models to describe the combustion: predicted, semi-predictive and non-predictive model.

7.5.1. Predictive and non-predictive

**Non-Predictive Combustion model:** In this model the burn rate is directly imposed as a simulation input. With a non-predictive combustion model, the burn rate does not depend on variables such as residual fraction or pre-combustion conditions. The fuel and air will simply burn at the prescribed rate. (In fact it is a very simplified model)

A non-predictive combustion model simply imposes a burn rate as a function of crank angle. This prescribed burn rate will be followed regardless of the conditions in the cylinder, assuming that there is sufficient fuel available in the cylinder to support the burn rate.
The burn rate will not be affected by factors such as residual fuel fraction or injection timing. This may be acceptable as long as the model is only used to study variables with little effects on the burn rate. For example, a model built to study the influence of intake manifold runner length on volumetric efficiency or a model built to study the acoustic performance of different muffler designs would not require any prediction of burn rate. In these cases, the variables of interest have a minimal effect on the burn rate.

**Predictive Combustion model:** In this model the burn rate is calculated from the appropriate inputs (pressure, temperature, equivalence ratio, residual fraction, etc.) and then applied in the simulation.

In principle, predictive combustion models are suitable for all simulations. But there are some drawbacks: The calculation time is substantially longer. Besides the added complexity of the calculations require more data, such as measured pressure profiles, significantly more time and more effort (the calibration of the model to measured data) to implement them in a model.

**Semi-predictive combustion model:** A normally non-predictive combustion can be modified GT-Power, so it’s semi-predictive. Then the calculation shall be based on the injection profile, air-fuel ratio, pressure and temperature. Therefore, the injector geometry and the injection pressure profile must be specified, since they affect the burn rate. This combustion model quickly becomes inaccurate. Therefore it should in some cases absolutely not to be used. For example by idling or by other diesel fuel and by EGR above 15%. This model is only useful as there is no measurement of the pressure profile. Is there a cylinder pressure is measured, there is a much higher accuracy to be achieved if they used a Non-predictive or Predictive combustion model.

\[^2\] GT-Suite *Engine Performance Application Manual*; page 46

### 7.5.2. Types combustion models

The following combustion models are available in GT-Power. They all have their own advantages and disadvantages. Here is a list of available combustion models:

- EngCylCombProfile
- EngCylCombDIWiebe
- EngCylCombDIJet
- EngCylCombMultiWiebe
- EngCylCombHCCI
- ArrayOfObjects
- RTLDependenceObjXYZ
- UserModel

The three most important combustion models will be explained in the appendix 3 ‘Combustion’. Because DIJet model is very important for our model, is this described in the next section. In the appendix are the formulas to read, to what extent has the GT-Power release.
EngCylComp DIJet (Predictive combustion model)

The Direct-Injection Diesel Jet Model (DIJet) is a predictive combustion model. The main objective of this model is to follow the fuel when it breaks into droplets, evaporates, mixes and burns. The total injected fuel is broken up into zones: 5 radial zones and many axial slices. Each zone contains subzones for liquid fuel, unburned vapour fuel, and entrained air, and combustion gases.

Figure 5, fuel injection

The total mass of fuel in all zones is equal to the specified injection rate (mg/stroke) divided by the number of nozzle holes. The DIJet model takes only one nozzle hole, assuming that all nozzle holes perform identically. Immediately after the injection point, the fuel subzone contains liquid fuel and all other subzones are empty. As the zone moves into the cylinder, the fuel breaks into droplets and begins to entrain air and to evaporate the liquid fuel, forming the unburned subzone. The velocity of the zone decreases, because the kinetic energy due to the energy consuming evaporation. The outer zones entrain air more quickly than the inner zones, thus decreasing their velocity more quickly and resulting in less penetration distance as can be seen in the figure immediately above.

The moment that an unburned zone starts to combust is dependent on:
- The cylinder pressure
- The zonal temperature
- The fuel-to-air ratio.

The zonal temperature is calculated from the temperature of the injected fuel, entrained air temperature, and the effects of the evaporating fuel.

The zonal fuel to air ratio is calculated from the masses of vapour fuel and air in the unburned subzone. During combustion the unburned fuel and air are burned and moved to the burned zone, further changing the temperature and composition. NOx and soot are calculated for each burned subzone taking into account the fuel-to-air ratio and temperature. The total cylinder NOx and soot are the integrated total of all of the individual burned subzones.

Zones are combined when the relative velocity causes a later zone to overtake an earlier zone. The difference in velocity of the zones results from differing injection pressure and the amount of air entrained. When zones combine they assume the earlier zone number.

GT-Power clearly shows, step by step, what formulas are used. The general formulas are simply derived from the ‘known’ laws of physics, and readable, other, more secret formulas and calculation procedures are not readable for third-party users.

This makes it impossible to check detailed the calculations. But the calculated values can always be compared with actual data (‘kenfeld’ measurements) and the effect of the calculations can always be tested by varying the input data.
This DIJet model consists of the various components and calculation procedures. The follow values are calculated:

- Injection
- Breakup
- Diameter size of droplets
- Penetration
- Swirl effect
- Air entrainments
- Fuel Evaporation
- Ignition Delay
- Combustion

**Injection**
The DIJet model generates several calculated values. Its starts from the base: the injection of fuel through an injector. It takes into account the construction of the injector: The number of the nozzles and their sizes. The injector (simulation of the injection) uses a pressure profile and the injected fuel mass. Along with the fluid density, the injector discharge coefficient calculated. GT-Power informed us that they do not want to give the exact calculation procedure. This calculation is the basis of the entire DIJet model and comes back in several calculations.

**Breakup**
The fuel proceeds as a jet column up to the breakup time where it disintegrates into many small droplets. This calculation procedure makes use of a nozzle diameter and length, the fluid density and the initial fuel jet velocity, as obtained from the injection calculation. Overall is there a breakup time multiplier. To multiplier the calculated value. The diameter of the droplets is calculated by the ‘Sauter mean diameter’.

![Figure 6, Break-up length](image)

**Penetration**
After the breakup time the fluid continues to penetrate with a reduced rate. The calculation starts with the calculated rate at the centreline based on the initial fluid velocity and the breakup time. But in the cylinder is a movement of air, this where called swirl. This makes the penetration distance grows. The actual penetration distance depended of engine speed and swirl ratio.
Ignition delay and Air entrainment

The combustion model is calibrated by five values. (The exact calculation procedure is not given by GT-Power). Appendix 3.5 ‘DIJet Combustion Calculations’ is the formulas that GT-Power has given. The values have to be calibrated are called multipliers:

- Combustion ignition delay multiplier (CIGN1),
- Combustion EGR delay multiplier (CIGN8),
- Multiplier. Before Combustion (CBAIR),
- Multiplier After Combustion (CAAIR),
- And Multiplier after impingement (CWALL).

The start of the combustion is clearly indicated by the initial, where the burn rate gets higher and a the line is increasing. The slightly "changing" pressure results in a request for fuel: Therefore a changing pressure profile will result in a continuously changing burn rate.

The combustion is described by a formula that is not published by GT-Power. We only know that three multipliers are used: CBAIR, CAAIR and CWALL. CBAIR describes the first part, the first peak. CAAIR describes the second part, the main combustion. The end is described by CWALL, but that portion of the combustion is not very interesting.

Figure 7, Example of changing the DIJet multipliers
**Fuel evaporation**

Once the droplets have broken up from the jet, it begins to evaporate resulting in a decreasing diameter. The evaporation rate can be boiling-limited or diffusion-limited. The Boling-limit of MDO has requested and obtained by Shell. The diffusion limited case depends on the velocity of the droplets relative to the velocity of the air. This relative velocity is an exponential decay with a time constant proportional \( D_d/v \). In GT-Power are functions included for the Droplet drag and droplet evaporation to multiplier this time constant and multiplier to the overall calculated evaporation rate.

**Combustion**

The calculation of combustion in the cylinder consists of three parts.  
1. the air/fuel mixing  
2. the energy content of the fuel droplet;  
   Directly after the point of injection the fuel has been divided into many small species, as described in previous paragraphs. Every droplet has its own size and it own speed, swirl and tumble. Each particle will now be calculated separately, or they from the unburned zone to the burned zone cab be transported. The moment that the pieces move from the unburned zone to the burned zone, is the Burn Rate.  
3. The ‘burned sub’-zone, which is the product of the combustion, from that point calculated GT-Power released the energy of that part. This is the calculated ‘Heat release’.

**8. Approach**

Before the engine model is build in GT-Power a lot of preparations got to be done. Searching for a lot of information and data from the engine. And practicing with GT-Power because the lack of experience with GT-Power or other GT-Suite applications.

**8.1. Tutorials**

There are different tutorials and examples for all engineering applications in GT-Power. However the main focus is only in GT-Power, so the engine performance tutorials are done to understand the GT-Power software package. These tutorials explain the basics of a simplified one cylinder engine model and how to run a full design of experiments (DOE) on a multicylinder turbocharger engine.

\[^3\text{GT-Suite Engine Performance Tutorials.}\]

**8.2. General numbers**

To fit the model to the existing SW280 engine a lot of input data is required. A lot of this information was already available from existing measurements and from original drawings made in the 1980’s when this engine was developed.
8.3. Drawing
All dimensions are from the drawings. All these drawings can be found in the archive of Wärtsilä Zwolle. Necessary drawings for the engine model are;

For the compression ratio and shape of the combustion space:
- Piston
- Cylinder head
- Connecting rod
- Crankshaft
- Engine block

For the intake system:
- Cylinder head
- Intake valves
- Receiver
- Air cooler
- Compressor
- Air filter
- All piping between these parts

For the exhaust system:
- Cylinder head
- Exhaust valves
- Exhaust manifold
- Turbine

For the fuel injection:
- The nozzles

8.4. Choose the right combustion simulation
For a proper simulation of the engine a well performing combustion module has to be used. GT-Power contains several modules with different characteristics and application areas. Using the model the user has first to decide which module is the most suitable for the application involved.

The different combustion models are already mentioned in chapter 7.5 Combustions whilst the full description is given in appendix 3 ‘Combustion’. The user has to select the right combustion model. This is depending on the data available and the required results. When the results perform only as non related performance the non-predictive model could be used. In all other cases the semi-predictive or predictive model has to be used.
8.5. Injection
Fuel injection is a complex system and not easy to simulate properly. On the other hand it needs a high accuracy because it is the main input for the combustion model. An adequate injection simulation needs a measured injection pressure as function from the crank angle and a total injected mass.

In the ‘Kenveld’ measurements the injection pressures have been measured as a function from the crank angle measured for all 32 measurement points. However, the pressure sensor was placed in the high pressure line just before the injector, resulting in a little shift in the crankangle signal. And the needle lift is also measured to determine the signal shift and determine the opening and closing pressure for the injector. The injected fuel mass has been calculated from the fuel consumption flowmeters. With these data it is possible to simulate all the 32 measurement points, All other operating points are much more difficult to simulate because there is no sufficient data available.

That could be solved with a fully predictive injection profile that is used in the latest version of GT-Power V7.2 build1. Because V7.1 build 5 is used in this model the injection profile remains a non-predictive.

8.6. Valve timing and lift
Another imported input for the flow through the engine is the valve timing and lift. A camshaft profile is measured but the camshaft profile is not the same as the valve timing and lift. The ratio between the camshaft profile and valve lift is caused by the rocket arms. And there is also a clearance between the valve and rocket arm causing a shift in the profile.

Besides the valve timing and lift that is measured, there has been also a measurement at Ricardo engineering when this engine was developed. In this measurement the discharge coefficient and swirl is measured as a function from the valve lift. This measurement is listed in Appendix 4 ‘Valve’s’.
8.7. Filter

The cylinder pressure is measured in the combustion area. However the data contain a lot of noise what has to be removed (filtered). Therefore the pressure signal is filtered with a harmonic analysis technique provided by Wärtsilä employees. This technique is a mathematical model that transforms the existing function into a function based on sinuses and cosines with a number of harmonic elements. By reducing the amount of elements the measurement noise is removed. See also figure 10 Harmonic analysis.

The main drawback is that filtering always results in (some) loss of information: The filtered signal consists of a large number of (symmetrical) sinuses. (The original wave line is sometimes found back in GT-Power.) During the calculating of the burn rate GT-Power supplies the pressure step by step. The pressure has really small pressure changes. This reacts directly with increased or decreased burn rate. This is shown in Figure 11 Harmonic line returns in calculated burn rate.

Figure 11 contain the burn rate as a function of the crank angle. It clearly shows the start of the combustion at ±15° angle. The waving curve of the burn rate before the combustion is caused by the modeling of the cylinder pressure. This model is based on a harmonic filtered pressure profile: The slightly "changing" pressure results in a request for fuel. Therefore a continuously changing pressure profile will result in a continuously changing burn rate.

Figure 10, Harmonic analysis

Figure 11, Harmonic line returns in calculated burn rate
8.8. Accuracy
The exact accuracy of all the measurements and calculations available is not known. But based on
the experience and knowledge, reliability between 98% and 99% has been assumed and used for this
study.

However exhaust gas pressures and temperatures are difficult to measure because of significant
pressure pulsations, so these measurements are less reliable. The pressure sensor of the combustion pressure measurement has been placed in the cylinder, but
there is a lot of noise, which a negative affect on the quality of the measurement.

There is another measurement point, just behind the exhausts valves. At these points air-
temperatures are measured as well, but the responses are slow; therefore it is impossible to
measure temperature pulses. On the other hand temperature measurements are good indicators for
the quality of all the cylinders involved: When all temperatures are equal, or at least fully
comparable, the cylinders perform well. In addition to these temperature indicators can be
uses to determine the effect of changing conditions on the exhaust temperature.

9. Building the full SW280 model
With all the knowledge and experience that has been collected about GT-Power, the full model is
build. First a rough model containing all the basic components has been built. Thereafter the
components used have been calibrated using the relevant actual data. Finally the model has been
optimised.

4 GTISE Help

9.1. Cylinder, crack shaft, valve and injection base
All dimensions and other mechanical properties are entered in the model for the cylinder and engine
crank train. Like the combustion chamber, the crankshaft, valves and injection. With all these basic
mechanical properties the engine block is complete. This will be verified by the cylinder peak
pressure without a fuel injection and valve timing diagrams.

9.2. Inlet and exhaust
The intake and exhaust are the main flow components besides the cylinder head and cylinder.
All the piping and receivers are one-dimensional simulated, but can be used as an input in a 3D
model.

The application in GT-Power for these flow components is called GEM3D, it transfers a 3D model to a
1D component for GT-Power. The input for GEM3D could be a 3D CAD part or a model description
with dimensions. GEM3D transfer the main properties to a 1D modeling item like a flow-split or
straight pipe. With a certain volume, flow area and dimensions. But there are some drawbacks:
complex shapes are difficult to convert to a 1D model. When a GEM3D model is converted into a 1D
model GT-Power simplifies the shape into a round pipe.

All the intake and exhaust components together complete the flow system through the engine.
For every component a discharge coefficient will be calculate to simulate the flow losses. This will be
verified by the pressure drop between compressor outlet and receiver pressure.
9.3. Data input
A simulation model cannot be functioning without adequate input data. This section describes how the data available are implemented in the GT power model.

9.3.1. Measurements SW280
The 'kenveld' data which has been used for the computer simulation contains 31 cases varying from 400 to 1000 rpm and from 21 to 1 bar BMEP (Brake Mean Effective Pressure) Appendix 1 'Kenveld measurement' contains an example.

9.3.2. Structure and data
The final model simulating the whole engine contains the following modules:
- Flow
- Mechanical
- Control
- General
- Thermal

A rough description of each module is given below;

Flow
The flow group contains all the flow components from intake to exhaust and the combustion area. It refers to all gas and fluid properties and the description of combustion description.

Mechanical
The mechanical group contains the crank train; mechanical references are the friction and inertia for the engine crank train.

Control
The control group contains all elements required to describe the fuel injection and intercooler efficiency.

Thermal
The thermal group contains all the thermal properties, required for all the heat transfer calculations and simulations in the model.

General
The general group contains all other components and references, like the arrays and xyz-tables as described in chapter 9.3.3 Array's and tables.

All components, references, array’s and xyz-tables are linked together in the model and for each simulation all flow, mechanical, control, general and thermal steps have to be recalculated.

9.3.3. Array’s and tables
An engine is a quite dynamic object containing a lot of moving parts. Most movements can be described as a function of the crank angle.
As an example, the valve lift, and all injection parameters could be described as a function of the crank angle and load. All these data have been collected in array’s, XY-tables and XYZ-tables to define 1D, 2D and 3D parameters creating the input required for a proper GT-Power simulation.
GT power has different control boxes to control parameters. Sensors and actuators will be used for different control options. For example the fuel control: during a calculation-run the sensor will record the crankshaft speed and send it to the control function: ‘FuelMass-Request’. (See figure 12; injection system in GT-Power, Part 93-01). In this control box the amount of injected fuel is chosen with as second parameter the fuel rack.

**Injection**

The engine runs at various operating points with speed and load as variable. Every operating point consists of an injected fuel mass, an injection profile and injection timing.

In the lower right corner of figure 12 is a ‘pedalPos’ (Fuel rack). The fuel rack and crankshaft signal input for the ‘fuel mass-request’. The output goes to the injector, the injection got injection timing and an injection pressure profile, dependent on speed.

To describe the injection properly there are 3 tables available:

- Injection mass
- Injection timing
- Injection profile

**Injection mass [XYZ-table]:**
The injection mass table consists of:
- X=engine speed [RPM];
- Y=Rack [mm];
- Z=fuelmass [mg/stroke]
The engine speed (CrackTrain) and rack (PedalPos) are the fuelmass.

**Injection timing [XYZ-table]:**
The injection time table consists of:
- X=engine speed [RPM]
- Y=fuel [mg/stroke];
- Z=delay [Angle]
The engine speed and fuel mass are the parameters for the injection delay.

**Injection profile [X XYTable-table]:**
X=fuel [mg/stroke]; XY-Table = injection profile measurement
The fuelmass in the XY-table is linked to an injection profile.
A explanation of the tables are presented in chapter 10.4 Injection timing
The tables are presented in appendix 5 ‘Injection’
9.4. Environment

The environment in the cylinder is an important parameter for a correct combustion. Because there are air swirls and tumbles in the inlet, what's has affect on the combustion in the cylinder. It is therefore important that this information should be entered as accurately as possible. The following paragraphs describe how this environment is calibrated. And how DIJet is set and calculated by a DOE-Run.

9.4.1. Full model

The Full model is the ultimate model were all components are collected into one model. The full model consists of many different parts, like a;
- Intake system
- Intake port and valves
- Cylinder with combustion chamber
- Exhaust port valves, exhaust system
- Injector
- Cooler
- Compressor
- Control input values.

All these components have their own settings. They come from measurements or calculations. These all have their own configuration. That means that the full model many consecutive configurations. It is therefore important that the values for the valve to coincide with the measured values. In this state of modulation multipliers can be used for the calculated value by fitting the measured values. When the fitting is well done, the environment before the valve is similar to the measured data.

9.4.2. Cylinder environment

The cylinder conditions are difficult to measure, the trapped air conditions will be an assumption. A few parameters could be measured like the amount of tumble and swirl, chapter 9.4.4. Swirl and tumble.

And the amount of trapped air, that is described in chapter 9.4.3, with the volume efficiency of the engine. A parameter that can’t be measured is the trapped air temperature at Intake valve closing.

This will be assumed with the Zinner formula:

\[ Aufladung von Verbrennungsmotoren. Grundlagen, Berechnungen, Ausführungen. Karl Zinner. \]
9.4.3. Volume efficiency
With the calibration of the DIJet the trapped cylinder conditions must be defined, as accurate as possible. The main parameter for the trapped conditions is the volume efficiency. Other parameters are swirl, tumble and trapped air ratio. The volume efficiency is calibrated using the cylinder lambda that is predicted by GT-Power. The volume efficiency is empirically determined. The volume efficiency is linear to the lambda so it could easily be specified by the next equation.

\[ \text{(2)} \]

9.4.4. Swirl and tumble
The swirl and tumble are second important parameters for the in cylinder conditions, and therefore important for the combustion. Swirl and tumble are created by the intake valves. So good modelling of the exact shape of the inlet port and valve are necessary. But that is rather difficult for GT-Power because all flow systems are one dimensional. Therefore the swirl and tumble will be entered as hard data.
The swirl and tumble are measured by Ricardo engineering when this engine was developed, the complete measurement is in appendix 4 ‘Valve’s’.

9.4.5. Discard coefficient
The intake and exhaust ports and valves exist of many difficult shapes and that is not simple to simulate in GT-Power. To simulate the intake and exhaust ports and valves the intake and exhaust ports will be simplified to straight round pipes with the correct flow area. And the discharge coefficient is set as fixed input.
These discharge coefficients could be simulated with CFD simulation software or with a measurement on a flow bench. In the measurement form Ricardo engineering the discharge coefficient is measured as a function from the valve lift. These measurements are good enough and reliable so the data could be used in the GT-Power model.
9.5. Combustion
Because the model has to be predictive there should be a DIJet model chosen. An explanation is given below.

9.5.1. DIJet
In chapter 7.5 Combustions is described how the DIJet functions. However, GT-Power did not release all the details about the DIJet. To calibrate the DIJet to the existing engine, 5 calibration parameters are set to fit them correctly to the entered operating points.

- Ignition delay multiplier (Cign1)
- EGR specifies ignition delay multiplier (cign8)
- Entrainment multiplier before combustion (cbair)
- Entrainment multiplier after combustion (caair)
- Entrainment multiplier after impingement (cwall)

These five parameters are just multipliers to fit the combustion to the existing engine. The first 2 multipliers are to calibrate the delay of ignition, and the last 3 multipliers are to calibrate to burn rate to the measured data.

The input for the DIJet calibration is a set of operation points in the entire speed and load range. There should be at least 20 operation points to calibrate the DIJet properly. For all operating points is a cylinder pressure signal needed that is calculated in to a burn rate. The measured burn rate and predicted burn rate from GT will be matched.

9.5.2. Calibrating the DIJet
At first the ignition delay will be calibrated through the entire speed and load range. The 2 multipliers that are used must be set are the ignition multiplier and EGR multiplier. Because the SW280 haven’t got an EGR system this multiplier will be set to 1. The ignition delay will be calibrated with a DOE setup for each operation point. To validate if the ignition multiplier is correctly used the start of the predicted burn rate must be at the same time as the calculated burn rate from the measured cylinder pressure. In Figure 13 optimise injection delay is a DIJet ‘Fuel Burn Rate – pred’ (pink) and the predicted burn rate ‘Fuel Burn Rate’ (red) shown. In this case, the DIJet starts too early with the burn rate.

![Figure 13, optimise injection delay](image-url)
With the correct ignition delay the next step is to calibrate the predicted burn rate to the calculated burn rate from the cylinder pressure. The 3 entrainment multiplier will be set for all operation points at once. So a large DOE setup is build with all operations point and pre-estimated value’s for the entrainment multipliers.

<table>
<thead>
<tr>
<th></th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cbair</td>
<td>0.8</td>
<td>1.2</td>
</tr>
<tr>
<td>Caair</td>
<td>0.25</td>
<td>0.45</td>
</tr>
<tr>
<td>Cwall</td>
<td>1.5</td>
<td>2.0</td>
</tr>
</tbody>
</table>

With a DOE-setup in this range, there is a long calculation time. Therefore, we used one of the three partial factorial designs (chapter 7.3.1 ‘DOE Setup’). In this case, a Latin hypercube, what exactly is described in appendix 2 ‘DOE-Setup’. With these designs, the calculation time increase. However to run a complete DOE-setup like this, it takes a few hours. All results will be plotted in DOE-post and the optimizer tool will generate an optimum for the 3 entrainment multipliers.

Ultimately the DIJet model is a model that calculates by itself how the combustion develops. But it’s not completely accurate, it remains an approach, which very well corresponds with reality, because it is a just mathematical model. Predicted values have always to be checked and be compared with actual, measured data.

9.6. Engine efficiency
The engine is a thermal conversion machine, all the incoming energy gets burned and only a minor part is used to generate the required-output energy on the engine crankshaft. All other energy is converted to heat in the cylinder, oil, coolant and exhaust gasses. In this chapter all thermal related calculations will be described.

9.6.1. Heat transfer in the combustion area
The heat transfer in the combustion area is described with the Woschni function. This Woschni function is a model in which the heat transfer is based on heat conduction. And with the simplification that there is no movement in the trapped cylinder conditions like swirl and tumble. In GT-Power are also other heat transfer models (based on the Woschni function as well) the movement in the trapped cylinder conditions, like swirl and tumble.
In this study the Woschni-GT function is used. It is based on the original Woschni function but with air movements in the cylinder.

6 “Internal Combustion Engine Fundamentals” Section 12.4.3, by John B. Heywood
9.6.2. Friction
The friction in the engine cranktrain is related to engine speed and cylinder peak pressure and, represents all the frictions between the following parts:
- Crankshaft–bearing
- Conrod big end-crankshaft
- Piston pin-Conrod- small
- Piston–cylinder.

\[
\text{FMEP} = \text{Friction} \quad \text{[Bar]}
\]
\[
\text{FMEP}_{\text{const}} = \text{Constant part for the FMEP} \quad \text{[Bar]}
\]
\[
A = \text{Peak cylinder pressure factor} \quad [-]
\]
\[
P_{\text{cylmax}} = \text{Cylinder peak pressure} \quad \text{[Bar]}
\]
\[
B = \text{Mean piston speed factor} \quad \text{[Bar s/m]}
\]
\[
C = \text{Mean piston speed squared factor} \quad \text{[bar s}^2/\text{m}^2]]
\]
\[
C_{p,m} = \text{Mean piston speed} \quad \text{[m/s]}
\]

With this function GT-Power recalculated the friction for every step. The three parameters A, B and C are empirically determined by changing input parameters and compare these with actual values.

9.7. Turbocharger
The last step of modelling the SW280 in GT-Power is simulating the turbocharger. This is also the most difficult part of simulating the engine because a turbocharger is quite sensitive to changes in conditions. It is essential to be sure that the complete engine model is working properly before attach the turbocharger to the engine. Inaccuracies and errors of the engine model will be enlarged by the turbocharger and affect properties such as exhaust gas temperatures or ambient conditions.

At first the compressor will be simulated, because there is a compressor map from the VTC 254 turbocharger that is mounted on the SW280 engine. See also figure 15 ‘VTC 254, SAE compressor map’ and a SAE file was generated using the data from figure 15. However, this compressor map was not accurate enough. Therefore we contacted ABB, the manufacture of the VTC 254 for additional information. They sent us a standardized SAE file, containing the information we needed.

9.7.1. Charge air Cooler
The air compressor compressed the air to a higher pressure, resulting in higher temperatures as well. All that heat has to be removed before the air is entering the receiver. This will be done by a charge cooler. The charge cooler is simulated by a control box.

The charge cooler (a standard shell-and-tube heat exchanger) itself is simulated as a set of many small tubes, of which the wall temperature is an input variable for the control box. In the control box is a XYZ-map with cooler efficiency, water temperature, and water flow, air temperature at inlet and air pressure. The wall temperature has to vary until the outlet temperature is correct. The outlet temperature is the difference between temperature inlet and water temperature multiplied with the efficiency:

![Figure 14, Construction of the cooling](image)
9.7.2. Compressor

The compressor properties are described in a standardized SAE compressor map. In that map are the massflow and pressure ratio plotted on the X and Y axis. Speed lines and efficiency fields are included as well.

Data for a compressor map could be giving in a *.SAE extension. This SAE format is simple *.txt file where the data is placed in 4 columns, at first reduced turbo speed in RPM, second reduced massflow kg/s, third pressure ratio and at last efficiency. The turbo speed and massflow must be corrected to 288 Kelvin and 1 bar ambient conditions. If the input data is measured in other conditions, GT-Suite could also correct these measurements to the standardized conditions.

After the compressor map data points is the surge line is described with the parameters reduced turbo speed, reduced mass flow and pressure ratio.

9.7.3. Turbine

If there is no SAE-turbine map, there can be a different way to create a turbine map. To make these, there is some data needed. With certain data and measured value’s, there can be a turbine map made with speed lines and efficiencies lines. For the turbine we received the following information:

<table>
<thead>
<tr>
<th>Turbinenspezifikation</th>
<th>πT</th>
<th>ηST, max</th>
<th>(Ut/C’0)opt</th>
<th>αt,0</th>
<th>dαt/d(Ut/C’0)</th>
</tr>
</thead>
<tbody>
<tr>
<td>vtc 254</td>
<td>1.5000</td>
<td>0.81695</td>
<td>0.61000</td>
<td>1.07362</td>
<td>-0.04036</td>
</tr>
<tr>
<td>85-05-29 / HZTL 51952/8</td>
<td>1.7500</td>
<td>0.81737</td>
<td>0.61000</td>
<td>1.10765</td>
<td>-0.04036</td>
</tr>
<tr>
<td>dt = 0,24096 m</td>
<td>2.0000</td>
<td>0.91696</td>
<td>0.61000</td>
<td>1.13270</td>
<td>-0.04036</td>
</tr>
<tr>
<td></td>
<td>2.2500</td>
<td>0.81535</td>
<td>0.61000</td>
<td>1.14782</td>
<td>-0.04036</td>
</tr>
<tr>
<td></td>
<td>2.5000</td>
<td>0.81171</td>
<td>0.61000</td>
<td>1.15511</td>
<td>-0.04036</td>
</tr>
<tr>
<td>Sd = 98,66 cm2</td>
<td>2.7500</td>
<td>0.90462</td>
<td>0.61000</td>
<td>1.15909</td>
<td>-0.04036</td>
</tr>
<tr>
<td>Ss = 132,53 cm2</td>
<td>3.0000</td>
<td>0.79405</td>
<td>0.61000</td>
<td>1.16078</td>
<td>-0.04036</td>
</tr>
<tr>
<td></td>
<td>3.2500</td>
<td>0.77917</td>
<td>0.61000</td>
<td>1.16247</td>
<td>-0.04036</td>
</tr>
</tbody>
</table>

Table 3, turbine specification

\[ \begin{align*}
\text{πT} & = 1.5000 \\
\eta_{ST, \text{max}} & = 0.81695 \\
(Ut/C’0)_{\text{opt}} & = 0.61000 \\
α_{t,0} & = 1.07362 \\
dαt/d(Ut/C’0) & = -0.04036
\end{align*} \]

\[ \begin{align*}
\text{πT} & = 1.7500 \\
\eta_{ST, \text{max}} & = 0.81737 \\
(Ut/C’0)_{\text{opt}} & = 0.61000 \\
α_{t,0} & = 1.10765 \\
dαt/d(Ut/C’0) & = -0.04036
\end{align*} \]

\[ \begin{align*}
\text{πT} & = 2.0000 \\
\eta_{ST, \text{max}} & = 0.91696 \\
(Ut/C’0)_{\text{opt}} & = 0.61000 \\
α_{t,0} & = 1.13270 \\
dαt/d(Ut/C’0) & = -0.04036
\end{align*} \]

With these turbine specifications there could be calculations made for an efficiency lines (η) and flow coefficients line (α). As a function of a speed related parameter (Ut/C’0). This can be made for all the pressures (πT). Based with these calculations and with measured data is it possible to create a turbine map. These calculations are in appendix 6 ‘Turbo’. The results of this turbine map are not accurate enough due to the low amount of measurement point for a turbine map.
10. Result
After completion the model has been calibrated is all the information available. The quality and the reliability of the model are demonstrated by the burn rates and cylinder pressures. The following results are without the turbocharger, because the turbine map is not accurate enough to predict the performance of the engine.

10.1. Burn rate / heat release
The figure 18 shows the burnrate (mg/deg) as a function of the position of the crank (°Angle). The figure only shows the relevant part of the combustion. There is a difference between burn rate and heat release. The burn rate indicates how many species are available to participate at that moment in the chemical reactions. The heat release is the result of the chemical reaction. In figure 16 it’s clearly visible.

Figure 17, Burn rate at 800 [rpm], the measured burn rate and DIJet predictive burn rate.

Figure 17 Burn rate at 800 [rpm] clearly shows the high quality of the simulation. Nevertheless there are some differences:
1. The measured burn rate fluctuates significantly more than the calculated burn rate. The smooth curve of the calculated output is caused by DIJet simulations.
2. The first peak (at -5° Angle) shows the largest difference between predictive and measured values. This has an effect on the predicted cylinder pressure as well.

The fluctuates of the measured caused by the harmonic filter. The harmonic filtered pressure profile has some very small variation. These variations will be enlarged in the burn rate. The predictive burn rate from the DIJet is a theoretical calculation from the model to appear on reality. The predicted burn rate and calculated from cylinder pressure burn rate are not complete equal to each other. The first peak is slightly bigger from the predictive so that’s why the maximum cylinder pressure is slightly higher. These details are faults in the DIJet model.
10.2. Cylinder Pressure

Figure 18 *Measured and DIJet pressure* shows the results of five simulations, (simulating the experiments 1477-1481). Each curve contains the predicted and measured pressure as a function of the position of the crank (°Angle). The corresponding operating conditions are given in Table 4 *numbers by cases 1000 rpm*. The engine operating at a constant ‘engine speed’ of 1000 RPM at different loads.

The model hits the actual test quite good. It describes very well the changing shape of the pressure curves at changing loads. The difference between measured and predictive pressure is less than 10%.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>1477</th>
<th>1478</th>
<th>1479</th>
<th>1480</th>
<th>1481</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load [%]</td>
<td>111</td>
<td>85</td>
<td>58</td>
<td>32</td>
<td>5</td>
</tr>
<tr>
<td>Power [kW]</td>
<td>1959</td>
<td>1493</td>
<td>1028</td>
<td>559</td>
<td>95</td>
</tr>
<tr>
<td>Engine speed [rpm]</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>BMEP [bar]</td>
<td>21.2</td>
<td>16.2</td>
<td>11.1</td>
<td>6.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Rack [mm]</td>
<td>34.20</td>
<td>28.50</td>
<td>23.10</td>
<td>17.00</td>
<td>9.00</td>
</tr>
</tbody>
</table>

Table 4, numbers by cases 1000 rpm
10.3. Stoichiometric calculation

To check the chemical reactions calculate in GT-Power some calculations have been carried out manually. The calculations are described in detail in appendix 3.6 ‘Fuel Calculations’. Some results are summarized below:

<table>
<thead>
<tr>
<th>Molecular weight</th>
<th>Fuel number of molecules</th>
<th>Air mass fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>C= 12,01</td>
<td>C= 7,1860</td>
<td>O₂=0,233</td>
</tr>
<tr>
<td>H= 1,008</td>
<td>H= 12,1816</td>
<td>N₂=0,767</td>
</tr>
<tr>
<td>O= 16</td>
<td>O= 0,0015</td>
<td></td>
</tr>
<tr>
<td>N= 14,01</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

7 ‘IUPAC Periodic Table of the Elements: 19 Feb 2010’

General Combustion

Stoich Air/Fuel Ratio

10.4. Injection timing

The quality of the results is mainly dependent on the injection time, which is the main parameter for the DIJet combustion model. The control of the injection profile works well. In the graph from figure 19 Working of injection map are four different profiles. These are plotted at four different loads. The table’s parameters in the table chose the right profile for each operation point.

Table 19a, fuel request

Table 19a, fuel request, contains the ‘fuel request’ (mg/stroke, z) as function of ‘engine speed’ (RPM, x) and the ‘Rack’ (mm, y).

Table 19b, injection delay

Table 19b, injection delay, contains the delay (°Angle, z) as a function of ‘engine speed’ (RPM, x) and ‘fuel request’ (mg/stroke, y).

Table 19c, profile

Table19c profile, contains the ‘requested fuel’ (mg/stroke, first column) and the corresponding pressure profile.

Figure 19 shows the typical mass flow rate by the pressure profiles numbers. 2, 5, 9 and 12.
As an example; **table 19a** shows that at an ‘engine speed’ of 800 RPM and a ‘rack’ of 25 mm; 1530 mg/stroke fuel is required. **Table 19b**, shows that at a ‘fuel request’ of 1530 mg and an ‘engine speed’ of 800 RPM, the ‘delay’ of injection has to -16°Angle.

Further **table 19c**, shows that for 1530 mg fuel a pressure profile ‘profile 9’ is given.

### 10.5. GT-01 ×

The ‘Kenveld’ measurements are always used to configure the model. Ultimately, the model has to reproduce these value’s. In the following table **5 GT-Power results against ‘Kenveld’ measurements** is a small group of values. These are the first five measurements, with a speed of 1000 rpm. These data are part of graph 10.2 Cylinder pressure. In Appendix 7 ‘GT-Power results against measured Kenveld’ the entire table.

<table>
<thead>
<tr>
<th>Input</th>
<th>Kenveld 1477</th>
<th>GT-Power 1477</th>
<th>Kenveld 1478</th>
<th>GT-Power 1478</th>
<th>Kenveld 1479</th>
<th>GT-Power 1479</th>
<th>Kenveld 1480</th>
<th>GT-Power 1480</th>
<th>Kenveld 1481</th>
<th>GT-Power 1481</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine speed [rpm]</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Inject fuel mass [kg/h]</td>
<td>409.6</td>
<td>409.6</td>
<td>314.2</td>
<td>314.2</td>
<td>225.8</td>
<td>225.8</td>
<td>136.8</td>
<td>136.8</td>
<td>53.1</td>
<td>53.1</td>
</tr>
<tr>
<td>Output</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power [kW]</td>
<td>1959</td>
<td>1970</td>
<td>1493</td>
<td>1466</td>
<td>1028</td>
<td>1001</td>
<td>559</td>
<td>526</td>
<td>95</td>
<td>90</td>
</tr>
<tr>
<td>BMEP [bar]</td>
<td>21.2</td>
<td>21.3</td>
<td>16.2</td>
<td>15.9</td>
<td>11.1</td>
<td>10.8</td>
<td>6.0</td>
<td>5.7</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Lambda [-]</td>
<td>2.11</td>
<td>2.19</td>
<td>2.27</td>
<td>2.27</td>
<td>2.37</td>
<td>2.36</td>
<td>2.65</td>
<td>2.69</td>
<td>4.99</td>
<td>4.60</td>
</tr>
<tr>
<td>Receiver</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total air flow [kg/s]</td>
<td>3.97</td>
<td>4.29</td>
<td>3.25</td>
<td>3.48</td>
<td>2.4</td>
<td>2.58</td>
<td>1.58</td>
<td>1.64</td>
<td>1.03</td>
<td>0.97</td>
</tr>
<tr>
<td>pressure [bara]</td>
<td>3.52</td>
<td>3.49</td>
<td>2.85</td>
<td>2.81</td>
<td>2.11</td>
<td>2.08</td>
<td>1.41</td>
<td>1.40</td>
<td>1.03</td>
<td>1.02</td>
</tr>
<tr>
<td>temp [°C]</td>
<td>50.5</td>
<td>51.3</td>
<td>42.6</td>
<td>48.6</td>
<td>36.2</td>
<td>43.8</td>
<td>32.5</td>
<td>38.2</td>
<td>31.8</td>
<td>33.4</td>
</tr>
<tr>
<td>Exhaust</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pressure [bara]</td>
<td>3.05</td>
<td>2.87</td>
<td>2.55</td>
<td>2.27</td>
<td>2.00</td>
<td>1.70</td>
<td>1.50</td>
<td>1.26</td>
<td>1.40</td>
<td>1.07</td>
</tr>
<tr>
<td>temp [°C]</td>
<td>516.5</td>
<td>467.9</td>
<td>474.5</td>
<td>440.6</td>
<td>444.0</td>
<td>418.9</td>
<td>387.5</td>
<td>390.5</td>
<td>237.5</td>
<td>269.2</td>
</tr>
</tbody>
</table>

*Table 5, GT-Power results against ‘Kenveld’ measurements.*

In the table the most value’s are well reproduced. But the air flow through the engine is by each case to much. This could mean that the model is still too much scavenging. The pressure in the exhaust is lower than in the ‘Kenveld’. So there is a lower back pressure in the exhaust. This will explain why there is too much air scavenging through the cylinder.

**Figure 20, 21 and 22** shows the results for 3 predicted values:
- **Power [kW]**  
  - Fig. 20 **Power in kW**  
  - Table 6 **Power in kW**
- **BMEP [Bar]**  
  - Fig. 21 **BMEP in bar**
  - Table 7 **BMEP in bar**
- **Lambda**  
  - Fig. 22 **lambda**
  - Table 8 **lambda**

In each figure, predicted values (GT-Power) are plotted against actual values ('Kenveld'). The three figures clearly show that for high speeds (more than 600 rpm) the model fits well. However for lower speeds the deviations become significant.

GT-Power recognises this and advise DJet not too use for low speeds. We got the impression that there new version also improve the quality of the predictions at lower speeds.

**Figure 22 lambda** further shows a systematic error for the lambda predicted at lower speed and lower loads (when the engine runs at 1 Bar BMEP.)
The power from GT-Power against ‘kenveld’:
In general, the results of the model are below the ideal line. But not more than 5%. Except a few points in lower speed. The equation and R-squared are:

<table>
<thead>
<tr>
<th>BMEP</th>
<th>GT-Power</th>
<th>kenveld</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000rpm</td>
<td>1.88</td>
<td>1.87</td>
</tr>
<tr>
<td>1600rpm</td>
<td>2.06</td>
<td>2.04</td>
</tr>
<tr>
<td>2000rpm</td>
<td>2.35</td>
<td>2.30</td>
</tr>
<tr>
<td>2500rpm</td>
<td>2.70</td>
<td>2.66</td>
</tr>
</tbody>
</table>

The BMEP from GT-Power against ‘kenveld’:
By general, the results of the model are below the ideal line. With a maximum deviation around 5%. With the exception of a few points in the lower speed.

<table>
<thead>
<tr>
<th>Lambda</th>
<th>GT-Power</th>
<th>kenveld</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.50</td>
<td>0.51</td>
<td>0.50</td>
</tr>
<tr>
<td>0.55</td>
<td>0.56</td>
<td>0.55</td>
</tr>
<tr>
<td>0.60</td>
<td>0.61</td>
<td>0.60</td>
</tr>
</tbody>
</table>

The third graph (Figure 22) shows for the lambda the same trend: At high speeds the model describes the actual data quite well, but at lower speeds the deviations become too large. In addition to this, the graph shows for BMEP = 1 bar a remarkable trend: The differences between actual and predicted are large, but the points form a straight line perpendicular on the Y = X line. Because, the exhaust pressure is higher than the inlet and measured values. The air scavenging goes the wrong way. This creates an internal EGR in the model. Result; lower lambda, than ‘Kenveld’
11. Recommendations

To improve the current model further more research and data is needed. In these recommendations is description how to make a model much faster and get faster some better results.

This chapter first describes the weaknesses of the model. This is done in a few steps. After these weaknesses the recommendations is written.

11.1. Weaknesses in model

Weaknesses in the model could be caused by the following factors, the model in GT-Power is build by components that are configured by measured data, and there will be always some incorrect data in it. With a tight schedule there is not always time to sort out small details and there was a limited experience and knowledge about GT-Power. All this factors cases some weaknesses, in the following chapters are the weaknesses discussed.

11.1.1. Inaccuracies in measured values

Inaccuracies in actual values are always caused by a combination of instrumental errors (the instruments used are never 100 % accurate) and the experimental errors (the person who did the measurement makes errors as well).

11.1.2. Reliability at lower loads

As already shown in the previous chapter the results of the model only fits very well at higher speeds (> 600 rpm). In fact the model cannot be used when the engine runs in idle.

11.1.3. Quality of the combustion model

The combustion itself is the heart of every combustion engine and therefore the combustion model is het heart of this model. This means that small deviations in the combustion model can have large effects on the total output. The whole combustion is determined by the inlet conditions and the injection time as already discussed in chapter 10.4 Injection timing.

11.2. Recommendations

To improve the current model more research and actual test data are required. In addition to this there are tools available to reduce the calculation time and to improve the quality of the output. Some potential improvements are discussed roughly below.

11.2.1. Flow objects

The most fastest and accurate way to model all the flow components is to use 3D CAD models instead of using manual calculations (as done so far). GEM3D (an application from GT-Suite) can convert 3 dimensional CAD models into simplified one-dimensional flow parts, suitable for GT-Power, without significant losses of information and accuracy.
11.2.2. DIJet

Gamma Technologies is still working on improved versions of DIJet. At the beginning of the project we used the most recent version of DIJet (V7.1 build 4). During the project V7.1 build 5 came available. Recently the version V7.2 build 1 (Nov 2011) and build 2 (Dec 2011) have been issued and became available for customers.

**Combustion/injection**

The current model (V7.1 build 5) contains pre selected operating points; for each operating point a lot of parameters have to be selected. The main parameters are *engine speed* and *injected fuelmass*; finally resulting in a calculated *power supply*. However, in principle, it is possible, to insert an injection controller in GT-Power with as an advantage that the required *power supply* will be an input which is much more user friendly. But in this case a predictive injection rate is required. Unfortunately, the version V7.1 did not contain this option. GT-Power included this in the most recent version, V7.2. It is strongly advised to implement this in the next version of the model.

**Engine running at lower speed**

We got the impressing that the newer versions of DIJet also improve the reliability of the model at lower speeds.

11.2.3. Turbo

The turbo part of the engine model consists of a compressor model and a turbine model. The compressor model has been built but additional calibrations are still required. The configuration of the turbine model has not been completed yet. For simulating the turbocharger a standardized turbine map is required. This turbine map has to be delivered by the Turbo supplier, ABB. Because of lack of time this has not been implemented yet. Therefore more time and effort is required to complete the turbo section of the model.

11.2.4. Library

This study clearly shows that GT-Power is a powerful tool for Wärtsilä. To use it more frequently and making it more user friendly an up-to-date software library is essential. This library should contain:

- Inlet and exhaust systems
- Camshaft and valves
- Cracktrains
- Cylinders
- Injection systems with predictive injection behaviour (GT-Power V7.2 or newer)
- Combustion tools
- Access to 3D CAD models
12. **Source list**


13. Conclusion

The aim for this project was to build an engine performance model in GT-Power, this model exist of smaller different modules; a combustion, cylinder, engine crank train, valve’s, intake and exhaust system, charge air cooler and a turbocharger.

This study clearly showed that GT-Power has developed and issued computer software that can be used to simulate the performance of diesel engines developed and marketed by Wärtsilä. In this study Wärtsilä’s SW280 has been simulated quite successful.

In fact this study contains a first trial to simulate this SW280, so more time and effort is required to complete the model and to improve its quality.

We appreciated very much the support of all Wärtsilä’s employees, especially the support of Engine Expert Sandor Portman and colleagues.