Tutorial 2:

Computation of engine output characteristics for a 4-stroke turbocharged diesel engine

The main objectives of the work:

1. To familiarize students with the advanced software for computing and optimizing diesel engine parameters and performance.
2. To demonstrate the characteristic change of key indicators and processes in the diesel engine affected by the change of engine operating regimes.

Additional objectives:

1. To demonstrate the sequence of actions for optimizing the engine boost pressure, combustion chamber configuration and nozzle geometry.
2. To demonstrate the sequence of actions for optimizing injection timing.

Required engine input data and operating parameters:

1. Number of cylinders and engine type (in-line, V-type, boxer, etc).
2. Bore and stroke dimensions
3. Compression ratio* (typically 13 ... 17)
4. Maximum RPM
5. Cooling system (liquid, air)
6. Engine application area
7. Boosting system (for simplicity it is usually recommended to use single-step turbocharging with cooling and without exhaust gas recirculation (EGR)).
8. Number of valves per cylinder
9. Maximum injection pressure (this is required for the assessment of engine robustness; combustion chamber configuration and injector nozzle geometry all depend on the level of injection pressure).

It is recommended that the above parameters be selected based on the existing engine specification. Students can select the engine specification by their own, provided that the above mentioned engine parameters are available. The compression ratio can be assigned in consultation with your instructor. Usually all required data can be found in the internet.

Software:

The engine performance computation and optimization should be conducted using DIESEL-RK software developed by Moscow Bauman Technical University. You have to download and install DIESEL-RK software on your personal PC or laptop from www.diesel-rk.bmstu.ru website and use it when you work outside the campus. You will be able to remotely connect to an external server of the software provider via internet.

The sequence of student actions for the project after the launch of the software

Step 1

Click  button and create a new project using **Wizard of New Project Creation**. Answer all the questions in **Wizard of New Project Creation**, assign engine geometric parameters, operational parameters, and select supercharging/turbocharging scheme. **Wizard of New Project Creation** will generate input file, set required empirical coefficients, compute and set basic dimensions for the air and fuel intake based on the statistical data and experience in engine design accepted in the industry. Further, the available data can be edited or used as default if some engine design and operation data are not fully available. To implement this step general engine information and/or specification is required. Engine specification example is shown in Table 1.

Table 1. JCB TCAE-129 engine specification

Parameter	Value
Number of cylinders and type	4 in-line
Bore and Stroke, (D/S)	106 / 135 mm
Compression ratio	17
Number of valves per cylinder	4
Cooling system	Liquid
Max power at nominal RPM	129 кW @ 2050 min^{-1}
Break mean effective pressure (BMEP) at nominal RPM	16.2 bar
Max Torque at RPM	690 Nm @ 1500 min^{-1}
Idling RPM	850 min^{-1}
Max rail pressure	More than 1000 bar

The value of the compressor pressure ratio at nominal RPM can be chosen from Figure 1 based on break mean effective pressure (BMEP).

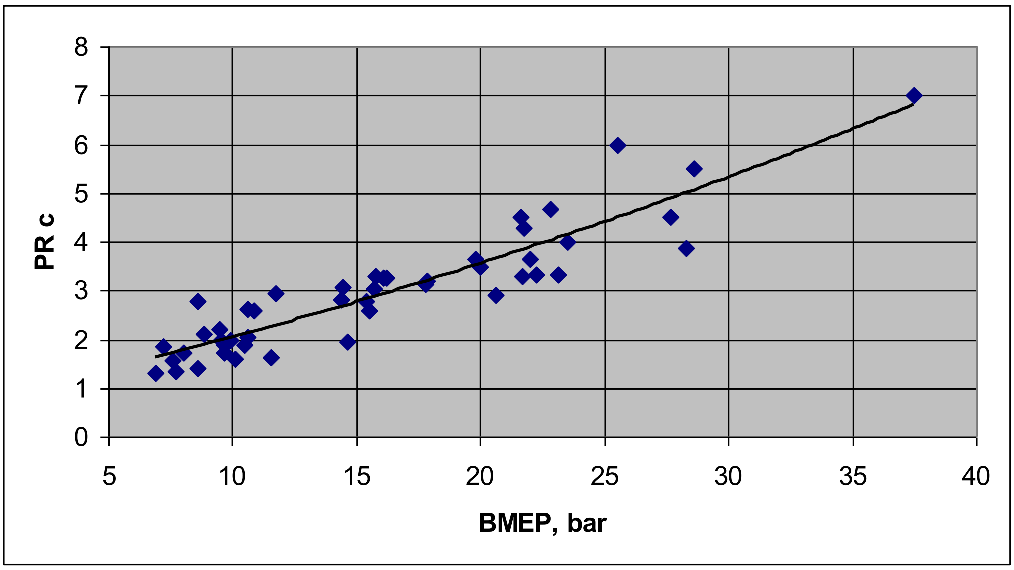


Figure. 1. Dependence of the compressor pressure ratio PRc at nominal RPM on BMEP.

When choosing the compressor pressure ratio it is recommended to assign higher values for modern engines with high maximum cycle pressure, as well as for the engines with strict restrictions on soot and NOx emissions. If the Miller cycle is used, then the boost pressure should be increased by approximately 25%. An additional increase in boost pressure is required by the EGR system: approximately 0.4 bar for every 10% EGR.

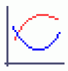
Wizard of New Project Creation will generate input file, set required empirical coefficients, compute and set basic dimensions for the air and fuel intake based on the statistical data and experience in engine design accepted in the industry. Further, the available data can be edited or used as default if some engine design and operation data are not fully available.

The **Wizard of New Project Creation** does not take into account the Miller cycle and the EGR system; the parameters for implementing these technologies must be set manually. It should be known that for EGR> 0.06 NOx emission should be calculated using a detailed chemical kinetics mechanism that is not included in the online version of the DIESEL-RK, but implemented only in the local version of the software. Also, the fuel multiple injection option is supported by the online version of the DIESEL-RK software (No.143) in a limited scope. It is recommended to set multiple injection function manually.

Step 2 Saving the project

Click  button and save the project in the working directory (folder). Save the data for each engine in a separate folder. Include the name of manufacturer and engine specification while giving a name for folders. This will help to easily identify the engine type.

Step 3 Setting the engine operating regimes

Click  button and edit the table for engine operation modes in accordance with the engine performance characteristics. Place the engine maximum power in column 1 and further gradually lower the RPM values in the next columns with the separate RPM for the maximum torque and RPM for the idling mode placed in the last column.

- For a given JCB TCAE-129 engine, the RPM increment should be set as: 2050; 1800; 1500; 1200; 850.

- Under the **Way of In-Cylinder Process Simulation** that is located in the upper left corner of the Operating Mode table shown in Figure 2, select the **"Specify Cycle Fuel Mass, [g]".**

- Calculate in the first approximation the cyclic fuel supply of a 4-stroke engine at full power mode according to the formula:

$$m_f = \frac{SFC \quad Power}{RPM \quad i_{cyl} \quad 30}; [\text{ g }]$$

where, *SFC* - specific fuel consumption [g/kWh] that can be selected from Table 2 based on the engine type; *Power* – engine power [kW], *RPM* – revolutions per minute of a crankshaft [min^{-1}], $\boldsymbol{i}_{cyl}$ – number of cylinders per engine. Insert the obtained cyclic fuel supply value in the Operating Mode table in Figure 2. The cyclic fuel supply for other regimes will be specified later.

- In the first approximation, for the max power regime set the fuel injection timing at 6 ÷ 8 deg. BTDC.

- Set the ambient air conditions (standard air temperature for aviation engines: T_o = 288 K, for other types of engines: 293 K or 298 K).

- Set the inlet pressure losses and differential pressure in the exhaust for the regime of max engine power. The maximum losses in the exhaust usually happen at full engine power regime and typically equal to 0.04 bar. The losses in the intake equal to 0.02 bar. These quantities for other regimes will be identified at a later stage.

Table 2. Approximate value of SFC and Turbocharger efficiency at max power for different types of diesel engines.

Engine type	SFC, g/kWh	η_{TC}
Engine for light passenger cars	235 ÷ 245	0.47
Engine for trucks and lorries with D ≈ 130 mm and BMEP ≈ 12	230 ÷ 235	0.49
Heavy duty engine with D ≈ 130 mm and BMEP ≈ 16	225 ÷230	0.51
Locomotive diesel with D ≈ 230 mm and BMEP ≈ 17	208 ÷ 215	0.53 ÷ 0.6
Generator diesel with D ≈ 130 mm and BMEP ≈ 22	203 ÷ 208	0.53 ÷ 0.57
Ship engine with BMEP ≈ 23	200 ÷ 210	0.58 ÷ 0.63

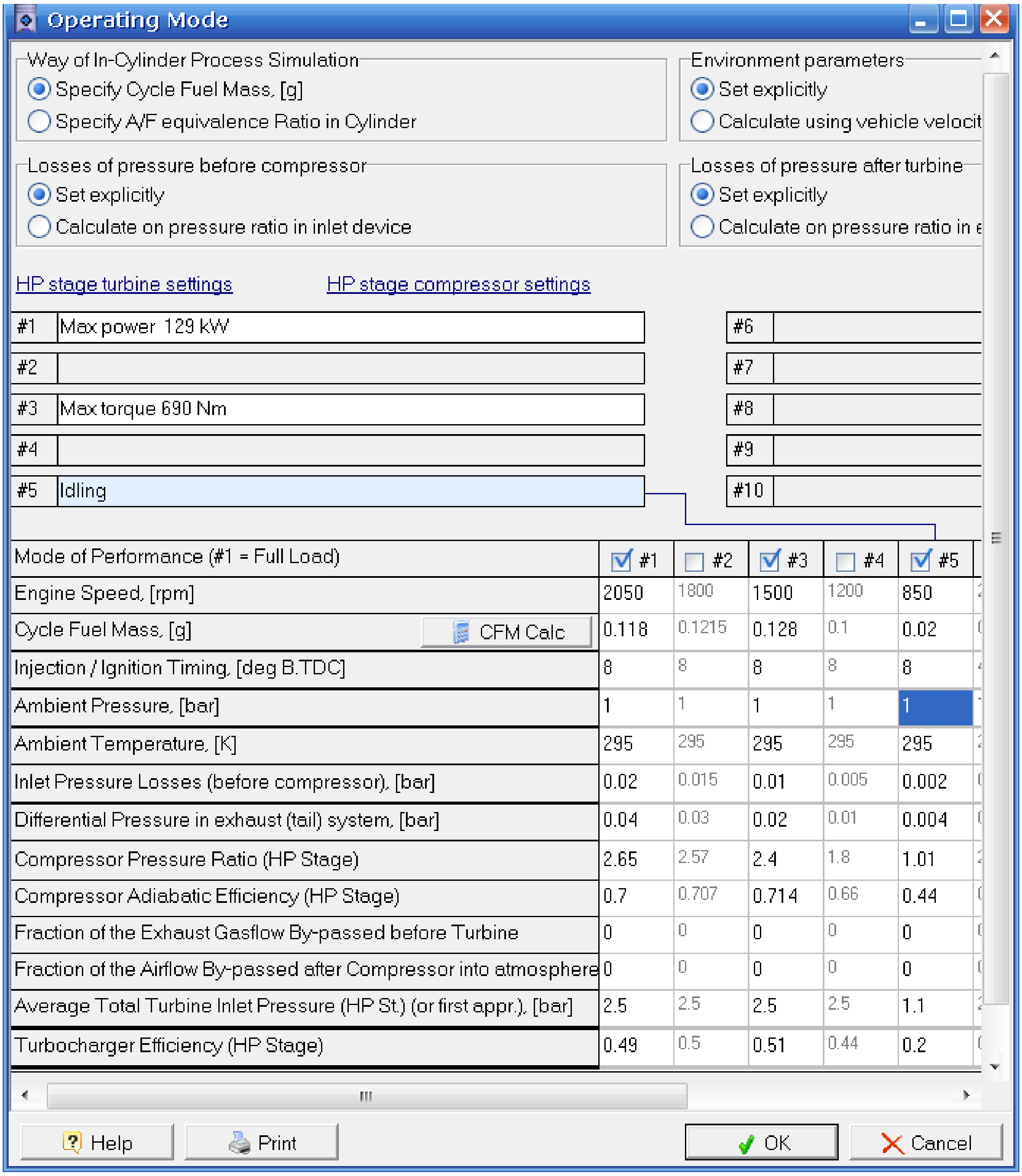


Figure 2. Operating Mode table

- Set in the first approximation the value for pressure before the turbine as equal or slightly less than the pressure after the compressor. The accuracy of the chosen value only affects the counting time. The pressure before the turbine will be determined by the program in an iterative calculation if the turbine and compressor power balance regime is given. This regime is given as default.

- Set the turbocharger efficiency η_{TC} for full power regime based on the value in Table 2. The compressor efficiency can be calculated as $\eta_C = \sqrt{\eta_{TC}}$. Efficiency for other regimes will be specified later.

Do not forget to write in the comment line a characteristic feature of each engine regime, this will help in the future. An example table of operating modes is shown in Figure 2.

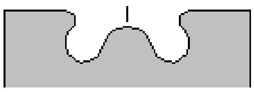
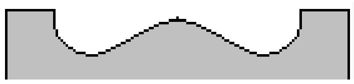
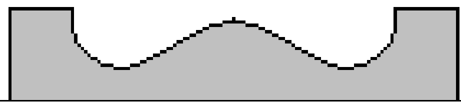
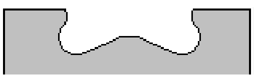
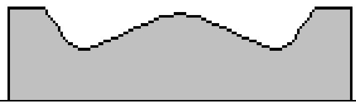
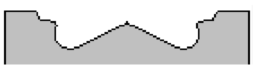
Remember that the preprocessor has an internal logic and the necessary windows and input spaces appear only if the relevant data is necessary for calculation of a selected type of engine.

Step 4 Check the correctness of the nozzle configuration and the shape of the combustion chamber.

Click:  and open **Fuel Injection System, Combustion Chamber** window.

- In the **Piston Bowl Design** window, check the settings for the combustion chamber configuration. Input the actual configuration of the piston cavity for the investigated engine, if available. If you don't have piston cavity configuration data then check the accuracy of pre-selected piston design made by the **Wizard of New Project Creation**. The optimum shape of the combustion chamber depends on the cylinder diameter and the degree of engine forcing. As the cylinder diameter and BMEP increase, the piston cavity becomes more shallow and open. Please see Table 3.

Table 3. The change of piston cavity based on different cylinder diameter of cylinder and BMEP.

BMEP	D_{cyl} < 100 mm	115 mm < D_{cyl} < 150 mm	D_{cyl} > 200 mm
10 bar			
17 bar			
25 bar			

In addition to the trend presented in Table 3, engines with low BMEP level, the cylinder diameter of less than 120 mm and the injection pressures of up to 800 bar may have deep piston cavities and alternative combustion chamber configurations, as shown in Figure 3.

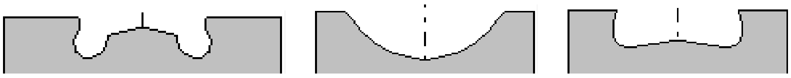
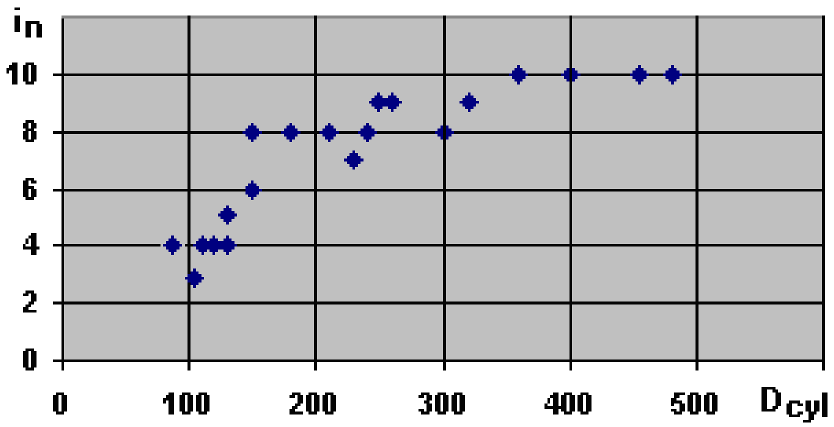
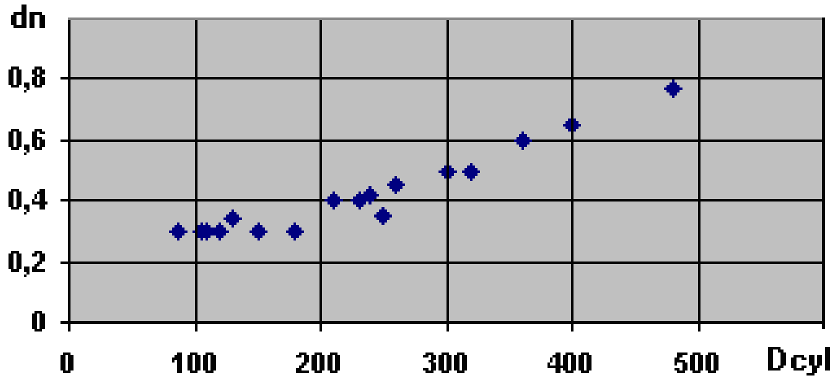


Fig. 3. Alternative combustion chamber configurations for naturally aspirated diesel engines with the cylinder diameter of up to 120 mm and the fuel injection pressure of up to 800 bar.

- In the **Injector Design** window, set the nozzle diameter and the number of nozzle holes and their orientation in the combustion chamber. The dependence of the nozzle number and orifice diameter on the cylinder diameter is shown in Figure 4.



a)



b)

Fig. 4. Dependence of (a) nozzle number, i_n, and (b) orifice diameter, d_n [mm], on cylinder diameter D_{cyl} [mm].

In modern high-speed diesel engines with a cylinder diameter less than 150 mm and injection pressure 1000 bar or higher, the nozzle orifice diameter can be reduced by 0.1 ÷ 0.15 mm and the number of nozzle orifices increased to 6 or 7.

The best and optimal orientation of the nozzle orifice is the one that ensures the maximum length of the jet development before the jet impinges the wall. You should change the spray angle α to adjust and ensure the free jet development.

Step 5 Check the correctness of the injection characteristics.

Click:  and open **Fuel Injection System, Combustion Chamber** window.

- Select the **Injection Profile** tab and for the Mode # 1 set the same cyclic fuel mass as the one in **Operating Mode** window. If the data on injection characteristics are available, set it on the shown graph. If the data are not available, just leave the injection characteristic as default or specify it as recommended for different fuel injection system shown in Table 4. Adjust the fuel injection duration in such a way that the maximum injection pressure p_{inj} corresponds to the fuel supply system of a given engine, as shown in Table 4.

Table 4. Fuel injection characteristics for different fuel supply systems

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p_{inj} ≈1200÷1600 bar, for modern engines with Common Rail system.


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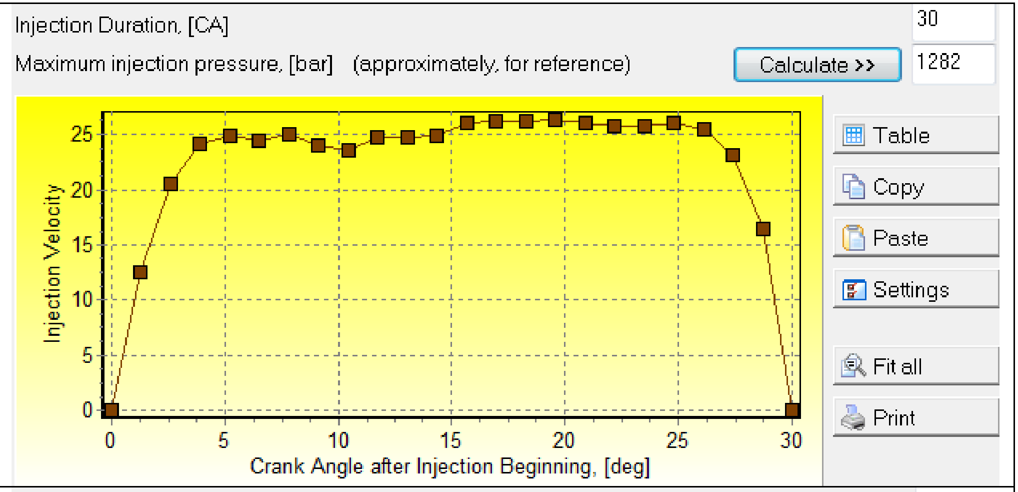

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p_{inj} ≈ 700÷1200 bar, for engines with split fuel delivery system.


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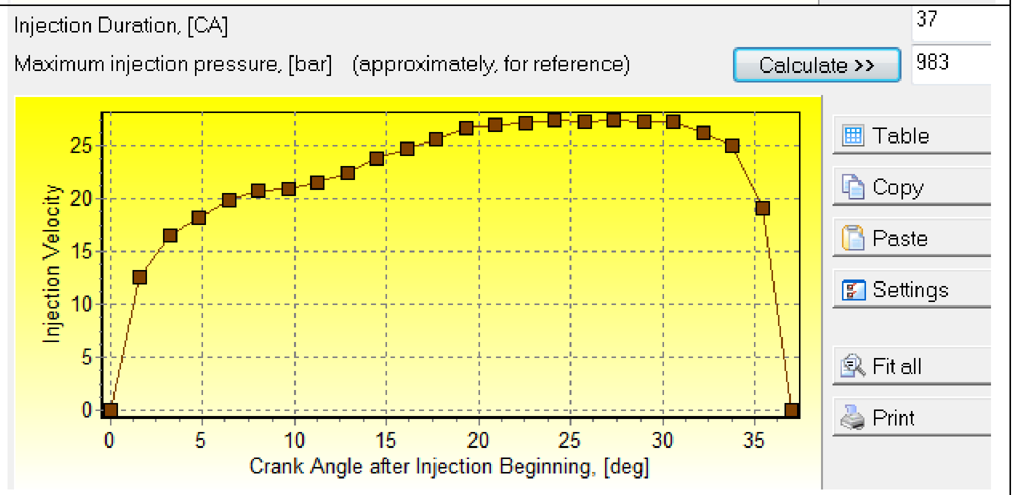

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p_{inj} ≈ 700÷1200 bar, for engines with pump-embedded injector.


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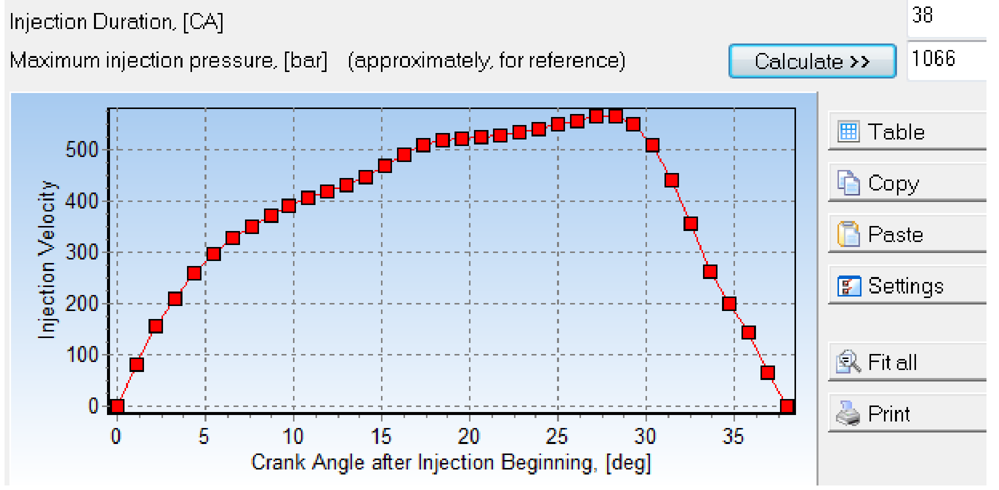

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</table>

In Table 4, the injection velocity scale on Y axis is conditional.

JCB TCAE-129 engine shown here as an example has a common rail fuel supply system, therefore, for this engine for fuel injection characteristics we should select the first option in Table 4. The injection pressure is set to 1550 bar.

Step 6 First calculation of full power mode

Click  button that starts the computation. In appeared window click **"ICE simulation"** button (only the mode for maximum power should be activated).

To verify the correctness of the input data perform the first calculation for one mode of "Maximum power".

For the computing of one mode (only this regime should be marked with a tick in the table of Figure 2) the following results are obtained:

- The table of integral parameters for an engine

- 1D graphs of various parameters versus time (crank angle degree)

- Visualization of spray in the combustion chamber for diesel engine

To investigate the individual operating modes the optimization and 1D and 2D scanning options can also be used.

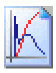
In the case of calculating the engine characteristics (if two or more modes marked with a tick in the table in Figure 2) engine output results are plotted vs RPM. Optimization and scanning for several modes simultaneously is not possible.

Therefore, at first, the analysis will be performed for each individual mode and then the entire engine performance characteristics can be determined.

Step 7 Analysis of the full power mode parameters

Computation results can be viewed and printed in Results section. For fast access to some sections of menu use the following buttons:

 To view engine integral parameters

 To view results in 1D format: the rate of heat release, gas exchange parameters, 1D scanning results, engine characteristics, etc.

When calculating the engine characteristics integral indicator table is not displayed. The table is only used to display the parameters of the engine on an individual mode.

To plot and view the engine characteristics use 1D view button or option <Results => Engine Performance>

To construct functions listed in the left pane, select the parameter and drag it using the left button of the mouse on one of the panels on the right side of the screen.

Plotting instructions are provided in the software tutorials.

- Check the value of the excess air factor α obtained in calculating the total power:

- For the transport diesel it must be within α = 1.75 ÷ 2.05.
- For the diesel generator α = 2 ÷ 2.2.

If no current data is available and α exceeds the specified limits, correct the boost pressure. The volumetric efficiency η_v should be in the range of 0.93 ÷ 0.98. If η_v <0.92, use the recommendations from the tutorial for computing the engine output characteristics of a spark-ignition engine.

- Check the calculated combustion duration φ_z. The value should lie within 70 ÷ 90 degrees. The combustion time can be adjusted by the value "y" in the "RK-model settings" window. If it is difficult to choose the empirical coefficients, leave the default settings given in the **Wizard of New Project Creation**.

Step 8 Optimization of the injection timing at the Maximum Power

Select 1D scanning: <Optimization => Scanning => Radio button 1D scanning>.
Select an argument for scanning: *Theta_i* (Injection Timing).
Click [>>] button and in appeared window insert:
- Min. Value *Theta_i*: 4 deg. before TDC,
- Max. Value *Theta*_i: 12 deg. before TDC,
- Number of calculating points: 5

Click OK close the window and perform scanning.

As a result, plot the effective power P_eng [kW] vs. Injection Timing Theta_i and also the Maximum Cylinder Pressure p_max [bar], the Maximum Rate of Pressure Rise dp/dTheta [bar/deg], and the Specific Fuel Consumption SFC [kg / kWh] vs. Injection Timing *Theta_i*, as shown in Figure 5.

Choose the optimal injection timing angle guided by the following considerations:

- The maximum cycle pressure for a transport engine with BMEP $\approx$ 16 should not exceed 170 bar: p_max <170 bar.
- The fuel consumption should be minimum SFC => MIN.
- The rate of pressure rise should not exceed the limit: dp/dTheta < 6.0 ÷ 6.5 bar/deg.

To satisfy these conditions 7 degrees before TDC is selected. The optimal injection timing angle at the full power mode is *Theta_i* = 7 degrees BTDC.
Fix this result as optimal and insert *Theta_i* = 7 deg. BTDC, as initial condition, in the Operating Mode table in Figure 2.

The power at such injection timing may exceed the required value of 129 kW. In such a case, to reduce the power, adjust the cyclic fuel supply so that the calculated power corresponds to the required value. To calculate the cyclic fuel supply, the following equation is used:

$$m_f = 0.118\frac{129}{131} = 0.1162 \text{ [g].}$$

Insert this value m_f=0.1162 (g) in the Operating Mode table shown in Figure 2.

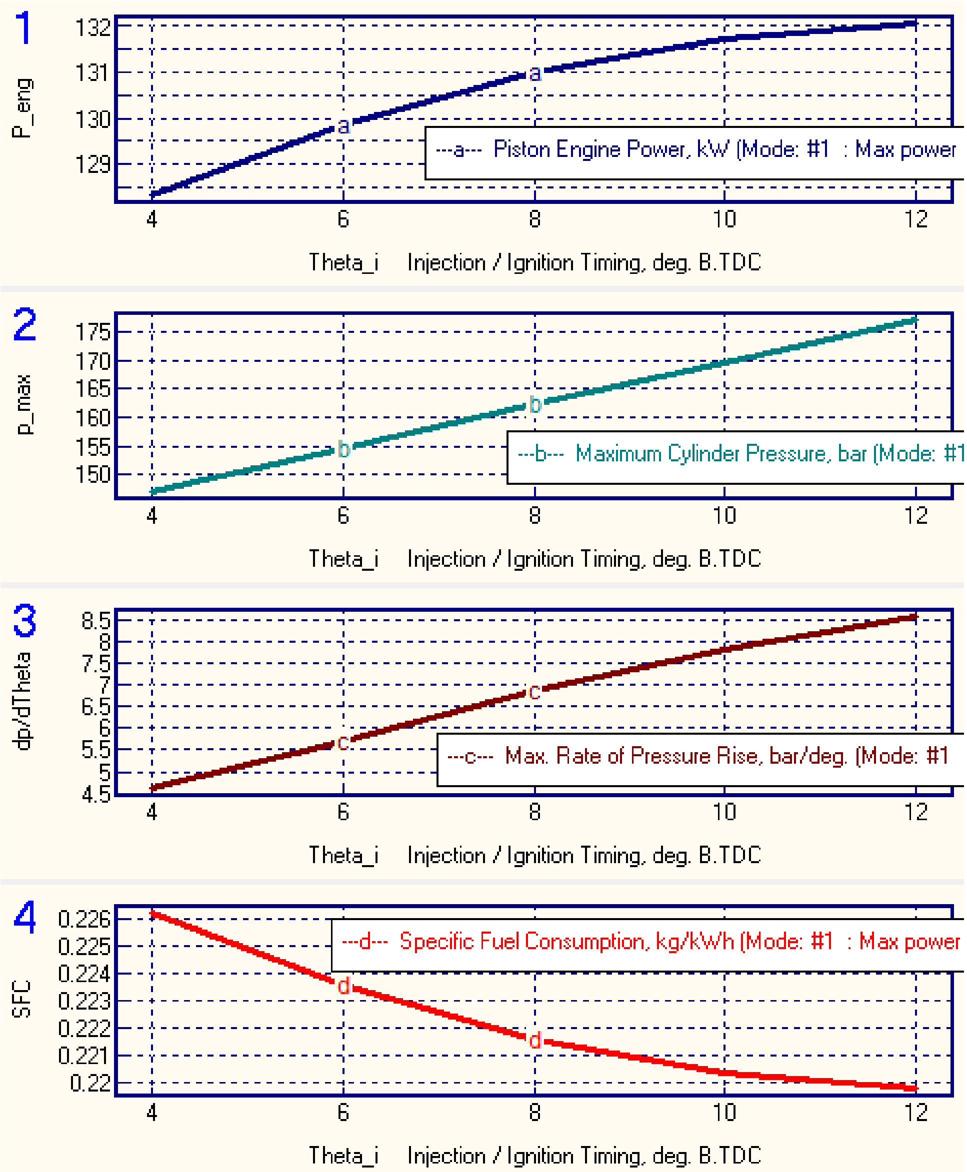
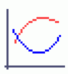


Figure 5. Dependence of the effective power P_eng, the maximum cylinder pressure p_max [bar], the rate of pressure rise dp/dTheta, and the specific fuel consumption SFC [kg/kWh] on the fuel injection Theta_i at full power mode.

Step 9 Calculation of the Maximum Torque

Set the cycle fuel mass [g] in Operating Mode  (Figure 2) for "Maximum Torque" regime using the proportion:

$$m_{f\,T\max} = m_{f\,P\max} \frac{T_{\max}}{T_{P\max}} 0.97 = 0.1164 \frac{690}{600} 0.97 = 0.1298 \text{ [g]}$$

where, the coefficient 0.97 takes into account the ratio of the specific effective fuel consumption at the maximum torque mode and at the maximum power mode; parameters T_{max} and P_{max} designate the mode of maximum torque and maximum power; T is the torque.

Modern engines usually use controlled boost. Compressor pressure ratio PRc_{Tmax} at maximum torque regime can be calculated as

$$PRc_{T\max} = 0.905\, PRc_{P\max}$$

where PRc_{Pmax} – compressor pressure ratio at maximum power regime, 0.905 – empirical coefficient that changes based on the boost control method.

The turbocharger efficiency at maximum torque regime exceeds that of maximum power regime by 1 ÷ 2%. The pressure loss in the exhaust and intake at maximum torque regime is half of that at full power. The initial pressure before the turbine can be set as 0.9 PRc_{Tmax}. Set these values in the Operating Mode table on Figure 2.

Set the injection characteristics for the maximum torque regime by analogy with Step 5, see above. The maximum injection pressure in this regime can be assumed to be the same as in maximum power regime if the engine has a common rail fuel system installed; Otherwise the maximum injection pressure at the non-nominal regime can be estimated by the equation:

$$p_{inj} = p_{inj\,P\max}\left(\frac{RPM}{RPM_{P\max}}\right)^{1.244}$$

where $p_{inj\ Pmax}$ – maximum injection pressure at maximum power.

Calculate the maximum torque regime.

Step 10 Optimization of the fuel injection timing at maximum torque

Select the 1D scanning : <Optimization => Scanning => Radio button 1D scanning>
Select the argument for scanning: Theta_i (Injection Timing).
Click [>>] and in the window that appears, specify:
- the minimum value of *Theta_i*: 4 degrees BTDC,
- the maximum value of *Theta_i*: 12 degrees BTDC,
- number of points: 5

Close the window by clicking OK button and perform the scanning.

As a result, plot the Specific Fuel Consumption SFC [kg/kWh] vs. Injection Timing *Theta_i*, and also the Maximum Cylinder Pressure *p_max* [bar] and the Maximum Torque [Nm] vs. Injection Timing *Theta_i*, as shown in Figure 6.

Choose the optimal fuel injection timing based on the following considerations:
- Maximum cycle pressure for a transport engine with BMEP $\approx$ 16 should not exceed 170 bar: *p_max* <170 bar.
- The fuel consumption should be minimum SFC => MIN.

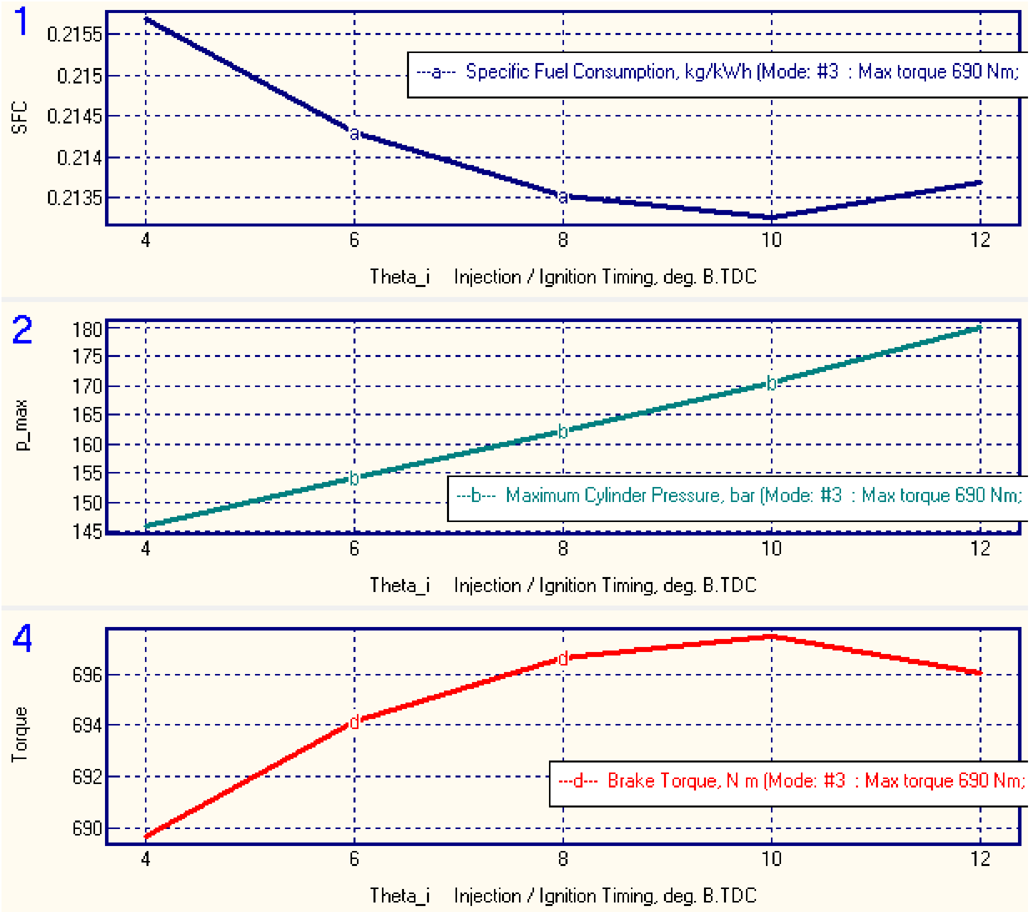


Figure 6. Dependence of the specific fuel consumption SFC [kg/kWh], the maximum cylinder pressure p_max [bar] and torque on fuel injection timing *Theta_i* at maximum torque regime.

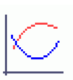
Analysis of the data in Figure 6 shows that the optimal injection timing angle at maximum torque is *Theta_i* = 8 degrees BTDC. (Although for *Theta_i* = 10 deg BTDC the fuel consumption is lower but the maximum cylinder pressure is almost 10 bar higher. For the engine design factor of safety and reliability, *Theta_i* = 8 degrees BTDC is chosen.
Fix this result as optimal, i.e. *Theta_i* = 8 degrees BTDC, and input them into the Operating Mode table in Figure 2.

In this example, the torque at the optimum point is 697 Nm. To bring the torque to the required level of 690 Nm, the cycle fuel mass m_f should be reduced to:

$$m_{fT\max} = 0.1298\frac{690}{697} = 0.1285 \text{ [g];}$$

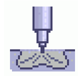
Insert this value to the Operating Mode table on Figure 2.

Step 11 Calculation of engine idling regime

Click on Operating Mode option  as in Figure 2 and set the column for engine idling regime.

Cycle fuel mass: $m_{f\ Idle} = 0.1\, m_{f\ T\max}$.

Inlet pressure losses: $dp_{int\_Idle} \approx 0.1\ \ dp_{int\_Tmax}$.
Differential pressure in the exhaust: $dp_{exh\_Idle} \approx 0.1\ \ dp_{exh\_\ Tmax}$.
Compressor pressure ratio: $PRc = 1.01$.
Average total turbine Inlet pressure: $p_T = 1.1$.
Turbocharger efficiency: 0.2.
Fuel injection timing $Theta\_i_{\_Idle}$ = 3 deg BTDC

Click **Fuel Injection System, Combustion Chamber** tab  and set the current cyclic fuel mass and injection characteristics at idling regime, as shown in Figure 7. Adjust the injection duration such that the maximum fuel pressure approaches $p_{inj\ Max} \approx 500$ bar (for Common Rail system). For split fuel injection systems, the maximum injection pressure should be calculated using equation (1).
The fuel injection characteristics at engine idling for all fuel supply systems can be set the same (Figure 7).

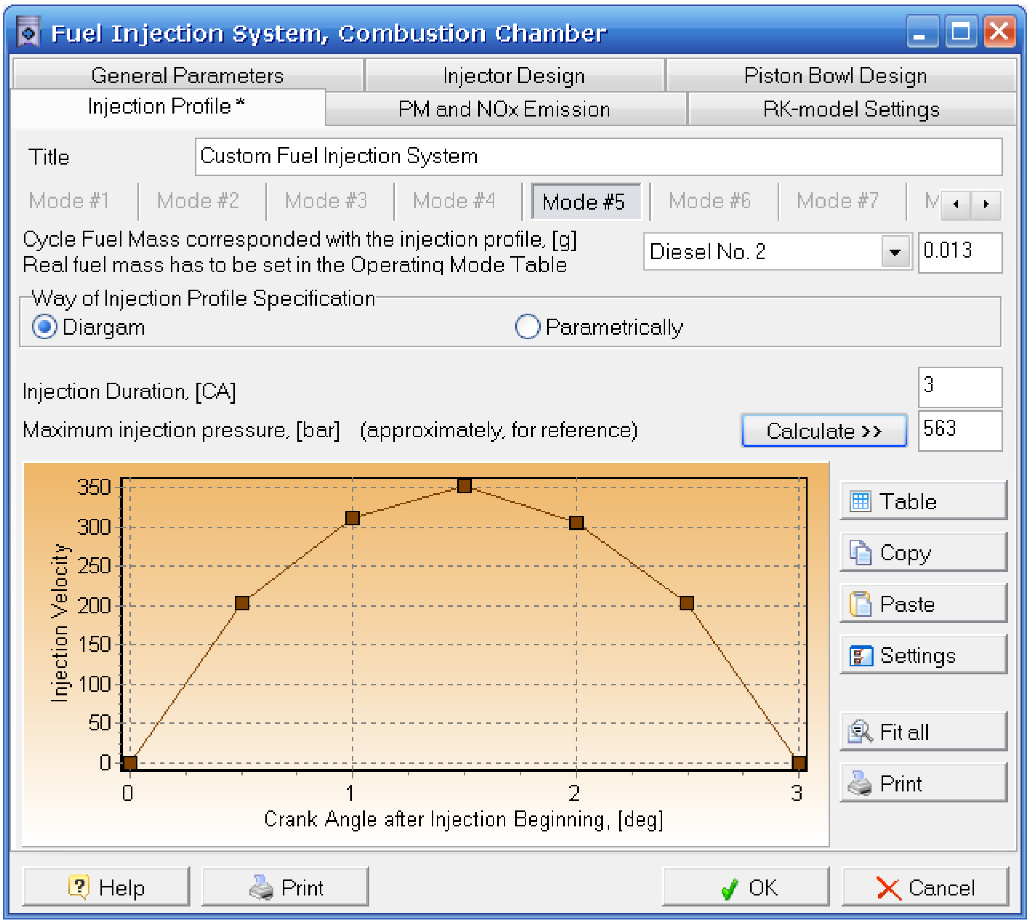
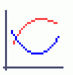


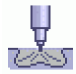
Figure 7. Fuel injection characteristics at engine idling regime.

Calculate the idling regime.

Step 12 Calculation of intermediate lower power regime.

Click on Operating Mode option  as in Figure 2 and set the column for engine intermediate regime.

Cycle fuel mass: $m_f = 0.74\, m_{fT\max}$.
Inlet pressure losses: $dp_{int} \approx 0.5\ dp_{int\_Tmax}$.
Differential pressure in the exhaust: $dp_{exh} \approx 0.5\ dp_{exh\_Tmax}$.
Compressor pressure ratio: $PRc = 0.833\ PRc_{\ Tmax}$
Average total turbine Inlet pressure: $p_T = 1.1\ \ PRc_{\ Tmax}$
Turbocharger efficiency: $\eta_{TC} = 0.85\ \ \eta_{TC\ Tmax}$.
Fuel injection timing $Theta\_i\_ = 0.5\ (Theta\_i_{Tmax} + Theta\_i_{Idle})$

Click **Fuel Injection System, Combustion Chamber** tab  and set the current cyclic fuel mass and injection characteristics at intermediate lower power regime, as shown in Figure 8. Adjust the injection duration such that the maximum fuel pressure is equal to the one at maximum torque regime (for Common Rail system). For split fuel injection systems, the maximum injection pressure should be calculated using equation (1).
The fuel injection characteristics for different fuel supply systems should be set based on Table 4.

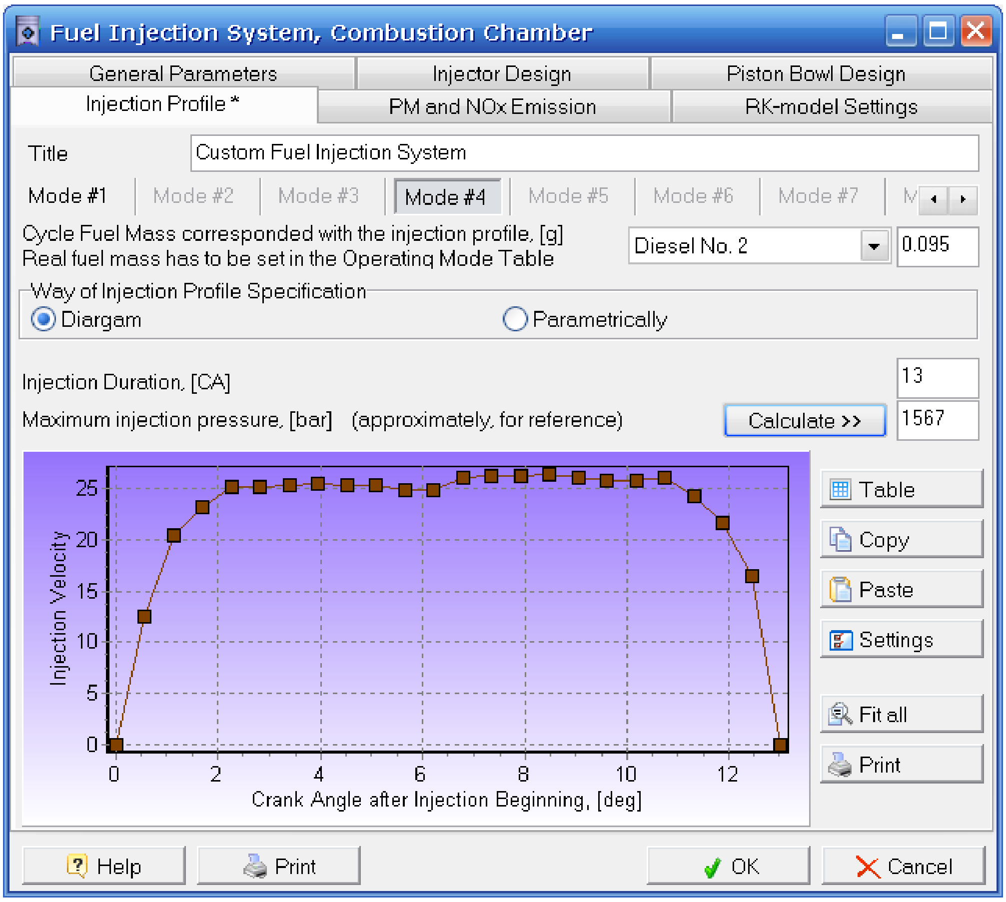
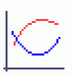


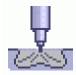
Figure 8. Injection characteristics for intermediate lower power regime (1200 RPM).

Calculate the intermediate lower power regime.

Step 13 Calculation of intermediate higher power regime

Click on Operating Mode option  and set the column for engine intermediate regime as shown in Figure 2

Cycle fuel mass: $m_f = 0.5\,(m_{fT\max} + m_{fP\max})$.
Inlet pressure losses: $dp_{int} \approx 0.75\ dp_{int\_Pmax}$.
Differential pressure in the exhaust: $dp_{exh} \approx 0.75\ dp_{exh\_Pmax}$.
Compressor pressure ratio: $PRc = 0.97\ PRc_{Pmax}$
Average total turbine Inlet pressure: $p_T = 0.83\ PRc$
Turbocharger efficiency: $\eta_{TC} = 0.5\ (\eta_{TC\ Tmax} + \eta_{TC\ Pmax}.)$
Fuel injection timing $Theta\_i\_ \approx 0.5\ (Theta\_i_{Tmax} + Theta\_i_{Pmax})$

Click **Fuel Injection System, Combustion Chamber** tab  and set the current cyclic fuel mass and injection characteristics at intermediate higher power regime, as shown in Figure 9. Adjust the injection duration such that the maximum fuel pressure is equal to the one at maximum torque regime (for Common Rail system). For split fuel injection systems, the maximum injection pressure should be calculated using equation (1).
The fuel injection characteristics for different fuel supply systems should be set based on Table 4.

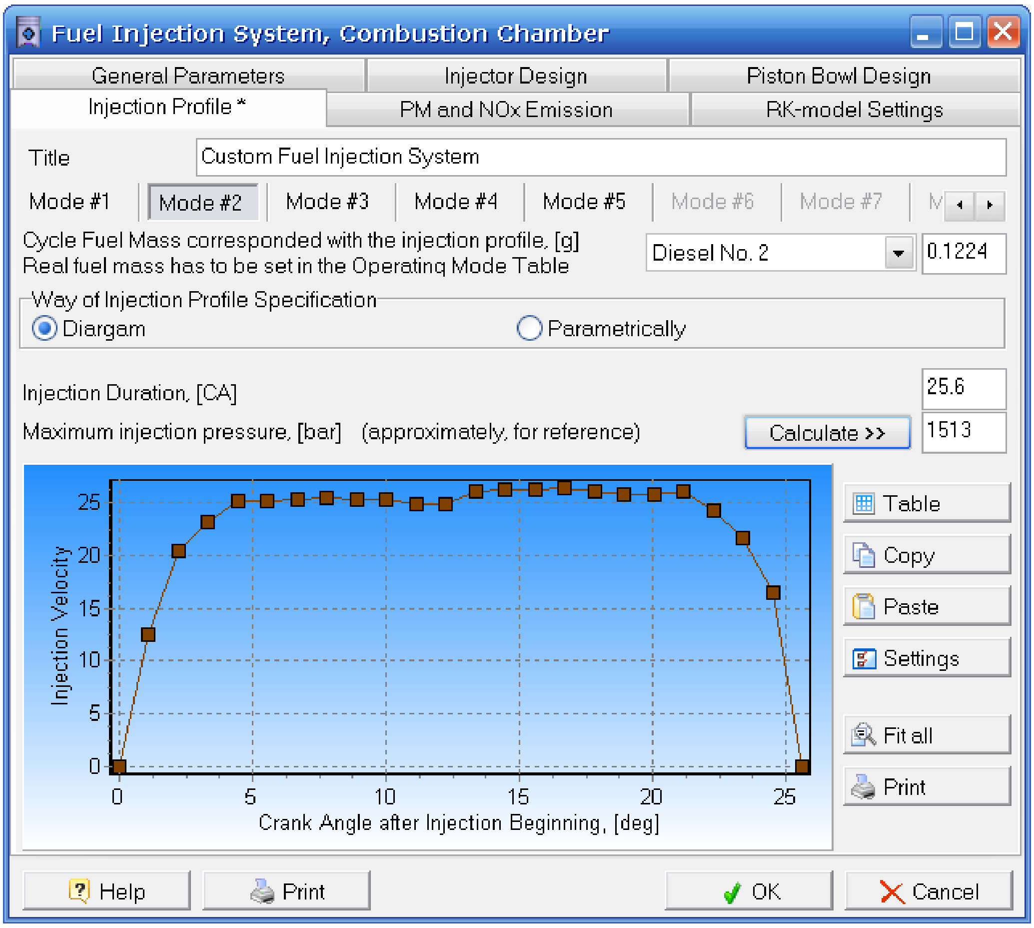
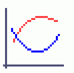


Figure 9. Injection characteristics for intermediate higher power regime (1800 RPM).

Calculate the intermediate higher power regime.

Step 14 Calculation of engine output characteristics

Click **Operating Mode** option  and set the columns for all engine regimes which have been preset earlier as shown in Figure 10.

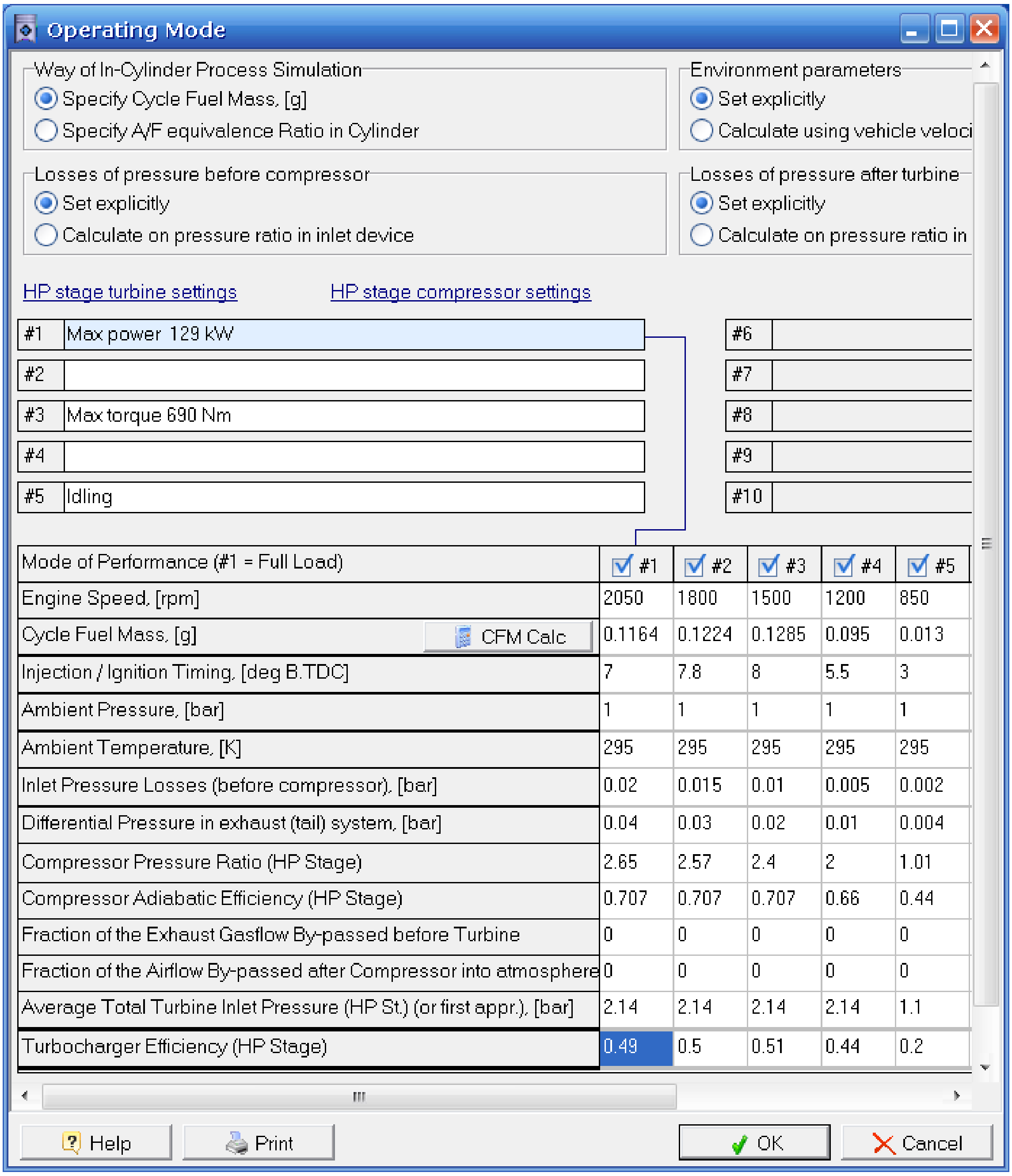


Figure 10. Settings for all regimes to calculate the engine output characteristics.

Calculate the engine output characteristics.

Construct the graphs for the following parameters vs. RPM as shown in Figure 11:

- Power, *P_eng* [kW].
- Torque, *Torque* [Nm].
- Break mean effective pressure, *BMEP* [bar].
- Specific fuel consumption, *SFC* [g/kWh], (Figure 11).

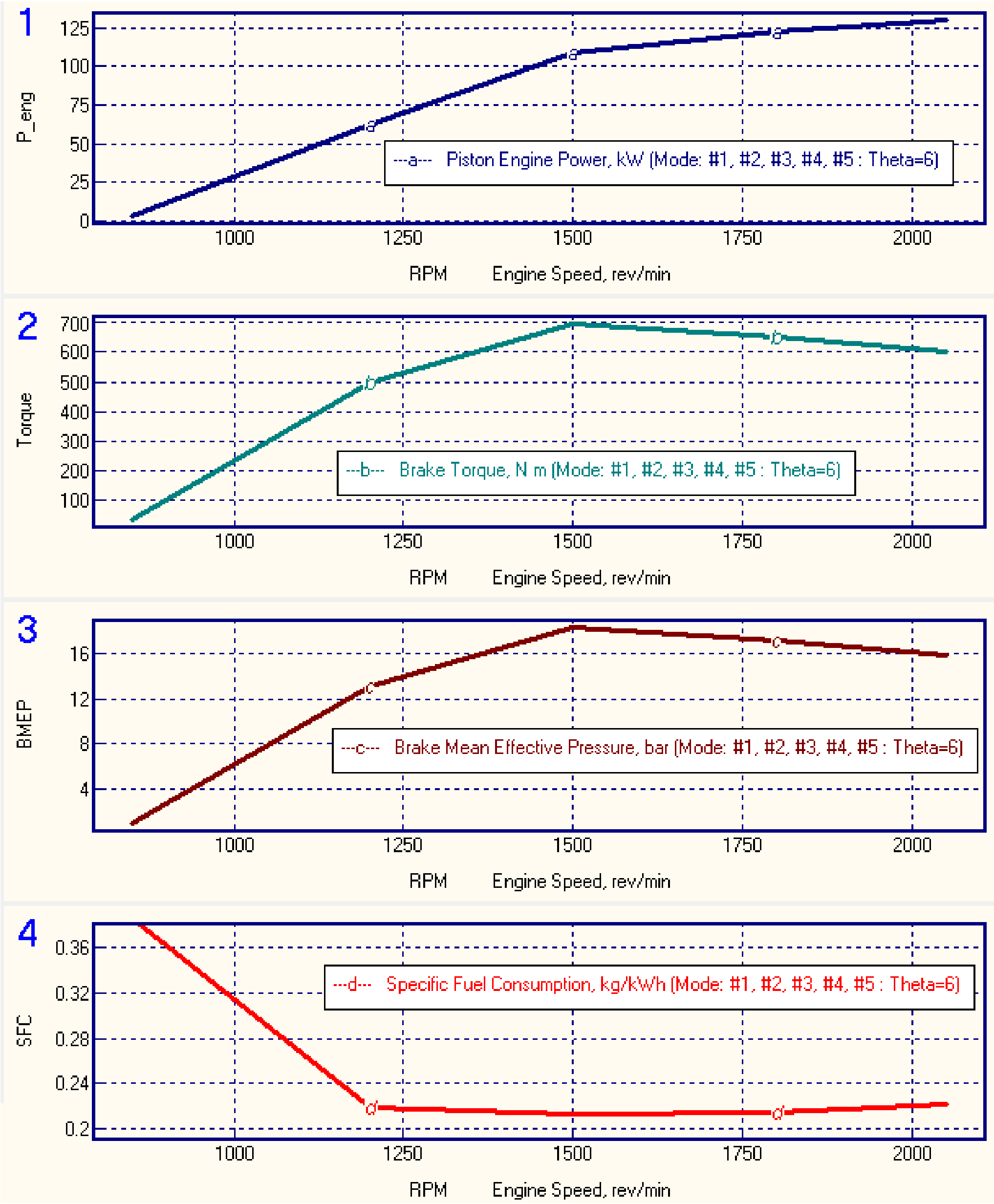


Figure 11. The change of engine parameters vs. RPM: (1) Power, *P_eng* [kW], (2) Torque, *Torque* [Nm], (3) Break mean effective pressure, *BMEP* [bar], (4) Specific fuel consumption, *SFC* [g/kWh]

Construct the graphs for the following parameters vs. RPM as shown in Figure 12:

- Compressor pressure ratio, *PR_c*
- Ait fuel equivalence ratio, *A/F_eq*.
- Fuel injection timing, *Theta_i* [deg. BTDC].
- Maximum cylinder pressure, *p_max* [bar]

Overall engine input and output parameters at different operating regimes are given in Appendix 1.

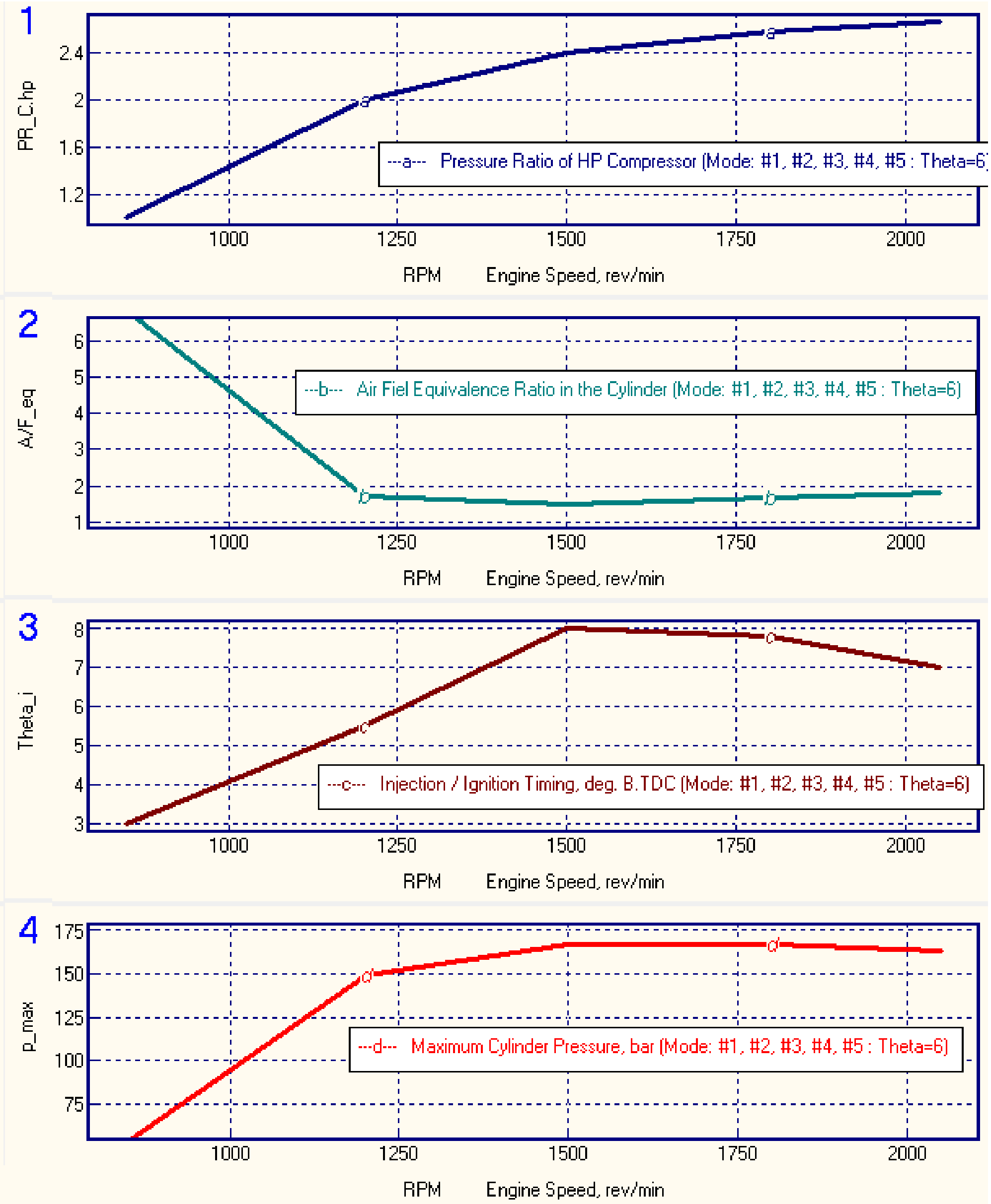


Figure 12. The change of engine parameters vs. RPM: (1) Compressor pressure ratio, *PR_c*, (2) Air fuel equivalence ratio, *A/F_eq*, (3) Fuel injection timing, *Theta_i* [deg. BTDC], (4) Maximum cylinder pressure, *p_max* [bar]

Step 13 Comparison of the results for the mixture formation, combustion and in-cylinder processes

Compute separately the engine operating regime at maximum power (RPM = 2050), maximum torque (RPM = 1500) and idling. Compare the in-cylinder pressure versus RPM and versus cylinder volume as shown in Figure 13, and the fuel injection velocity and the rate of heat release versus crank angle degree as shown in Figure 14.

Figure 15 shows the visualization results of the calculated fuel spray penetration at, (a) maximum power, (b) maximum torque, and (c) idling.

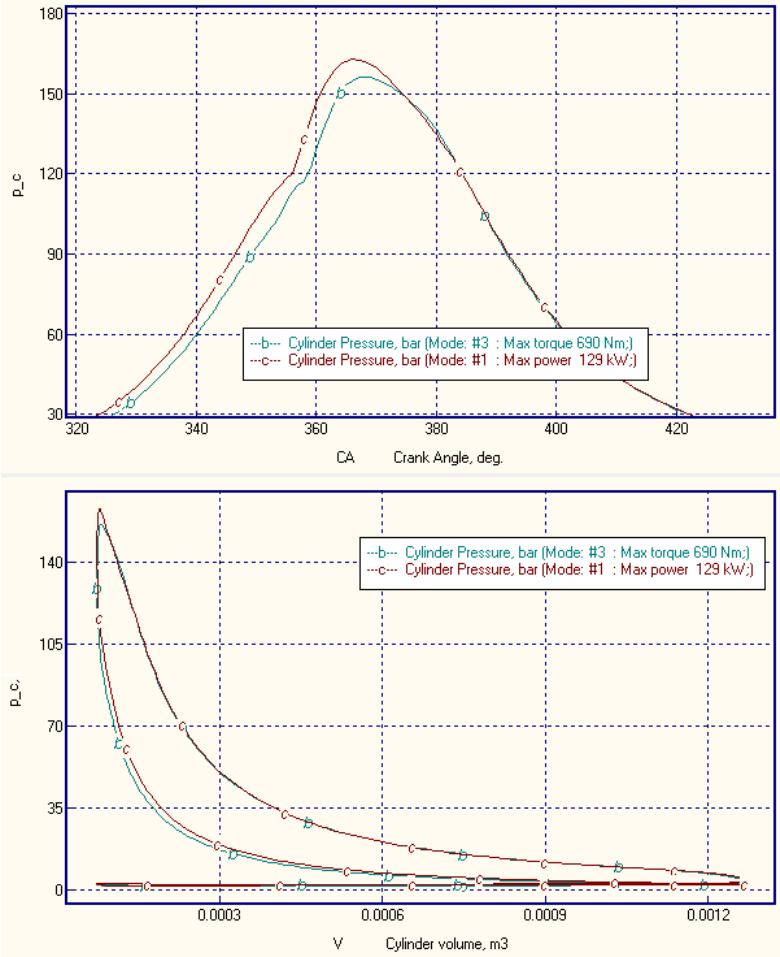


Figure 13. Comparison of in-cylinder pressure diagrams [bar] as a function of RPM and cylinder volume.

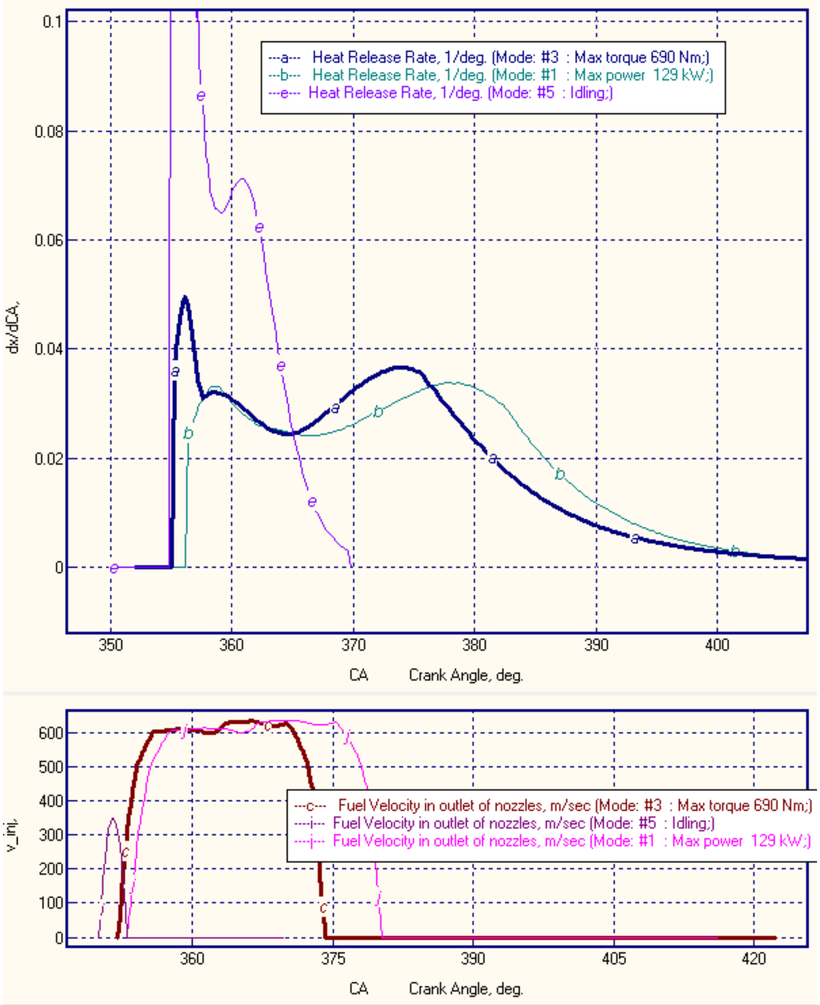
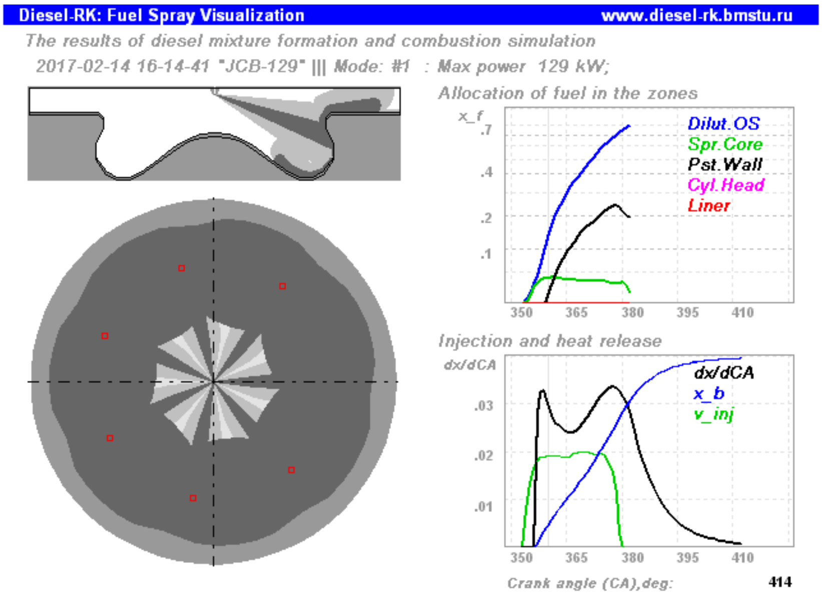
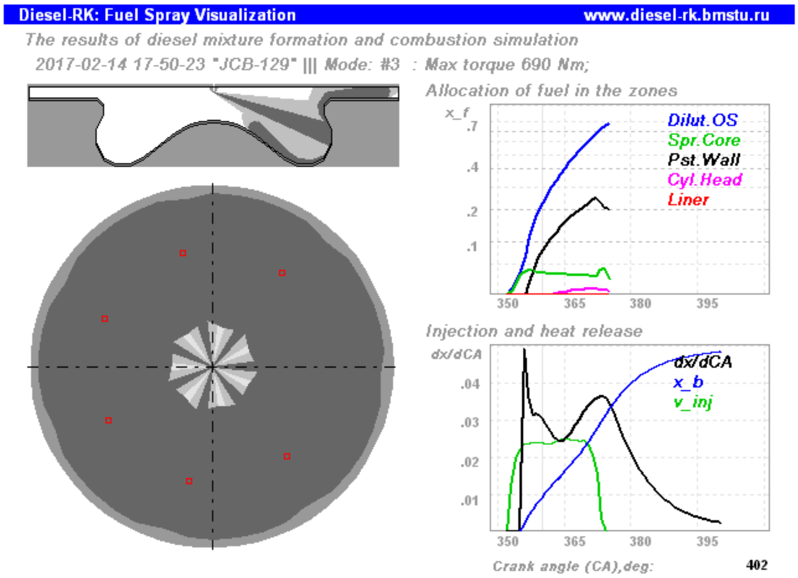


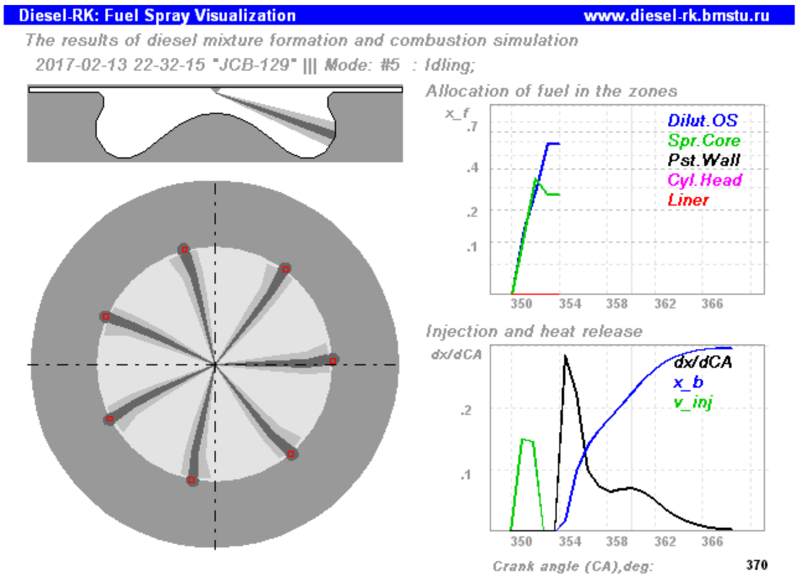
Figure 14. Comparison of the rate of heat release, *dx/CA*, and the fuel injection velocity, *V_inj* [m/s], as a function of RPM. The highlighted line corresponds to the maximum torque regime.



a)



b)



c)

Figure 15. The results of spray penetration at (a) maximum power, (b) maximum torque, and (c) idling.

Appendix 1

2017-02-14 16-14-41 "JCB-129" Engine characteristics at maximum power regime

```
 Mode: #1  : Max power  129 kW;
  Fuel:      Diesel No. 2

   ----------------- PARAMETERS OF EFFICIENCY AND POWER ----------------
   2050.0     - RPM      - Engine Speed, rev/min
   129.86     - P_eng    - Piston Engine Power, kW
   15.952     - BMEP     - Brake Mean Effective Pressure, bar
   604.95     - Torque   - Brake Torque, N m
  0.11640     - m_f      - Mass of Fuel Supplied per cycle, g
  0.22050     - SFC      - Specific Fuel Consumption, kg/kWh
  0.38415     - Eta_f    - Efficiency of piston engine
   19.067     - IMEP     - Indicated Mean Effective Pressure, bar
  0.45918     - Eta_i    - Indicated Efficiency
   2.6191     - FMEP     - Friction Mean Effective Pressure, bar
  0.83659     - Eta_m    - Mechanical Efficiency of Piston Engine

   --------------------- ENVIRONMENTAL PARAMETERS ----------------------
   1.0000     - po_amb   - Total Ambient Pressure, bar
   295.00     - To_amb   - Total Ambient Temperature, K
   1.0400     - p_Te     - Exhaust Back Pressure, bar (after turbine)
  0.98000     - po_afltr - Total Pressure after Induction Air Filter, bar

   ------------------ TURBOCHARGING AND GAS EXCHANGE -------------------
   2.5470     - p_C      - Pressure before Inlet Manifold, bar
   328.49     - T_C      - Temperature before Inlet Manifold, K
  0.20620     - m_air    - Total Mass Airflow (+EGR) of Piston Engine, kg/s
  0.48989     - Eta_TC   - Turbocharger Efficiency
   2.6091     - po_T     - Average Total Turbine Inlet Pressure, bar
   826.81     - To_T     - Average Total Turbine Inlet Temperature, K
  0.21042     - m_gas    - Mass Exhaust Gasflow of Pison Engine, [g/s
   1.7887     - A/F_eq.t - Total Air Fuel Equivalence Ratio
  0.55905     - F/A_eq.t - Total Fuel Air Equivalence Ratio
 -0.49664     - PMEP     - Pumping Mean Effective Pressure, bar
  0.95098     - Eta_v    - Volumetric Efficiency
  0.03185     - x_r      - Residual Gas Mass Fraction
  0.98623     - Phi      - Coeff. of Scavenging (Delivery Ratio / Eta_v)
  0.15137     - BF_int   - Burnt Gas Fraction Backflowed into the Intake, %
   1.7764     - %Blow-by - % of Blow-by through piston rings

   -------------------------- INTAKE SYSTEM --------------------------
   2.5279     - p_int    - Average Intake Manifold Pressure, bar
   331.04     - T_int    - Average Intake Manifold Temperature, K
   334.03     - Tw_int   - Average Intake Manifold Wall Temperature, K
   115.61     - hc_int   - Heat Transfer Coeff. in Intake Manifold, W/(m2*K)
   292.77     - hc_int.p - Heat Transfer Coeff. in Intake Port, W/(m2*K)

   ------------------------- EXHAUST SYSTEM --------------------------
   2.5994     - p_exh    - Average Exhaust Manifold Gas Pressure, bar
   826.03     - T_exh    - Average Exhaust Manifold Gas Temperature, K
   46.351     - v_exh    - Average Gas Velocity in exhaust manifold, m/s
   14.229     - Sh       - Strouhal number: Sh=a*Tau/L (has to be: Sh > 8)
   735.13     - Tw_exh   - Average Exhaust Manifold Wall Temperature, K
   124.54     - hc_exh   - Heat Transfer Coeff. in Exhaust Manifold, W/(m2*K)
   1027.2     - hc_exh.p - Heat Transfer Coeff. in Exhaust Port, W/(m2*K)

   --------------------------- COMBUSTION ----------------------------
   1.8138     - A/F_eq   - Air Fiel Equivalence Ratio in the Cylinder
  0.55134     - F/A_eq   - Fuel Air Equivalence Ratio in the Cylinder
   162.72     - p_max    - Maximum Cylinder Pressure, bar
   1841.3     - T_max    - Maximum Cylinder Temperature, K
   6.0000     - CA_p.max - Angle of Max. Cylinder Pressure, deg. A.TDC
   28.000     - CA_t.max - Angle of Max. Cylinder Temperature, deg. A.TDC
   7.2773     - dp/dTheta- Max. Rate of Pressure Rise, bar/deg.
  Injection: Custom Fuel Injection System
   1679.7     - p_inj.max- Max. Injection Pres. (before nozzles), bar
   9.2819     - d_32     - Sauter Mean Diameter of Drops, microns
   7.0000     - Theta_i  - Injection / Ignition Timing, deg. B.TDC
   27.149     - Phi_inj  - Duration of Injection, deg.
   3.3295     - Phi_id   - Ignition Delay Period, deg.
  0.04149     - x_e.id   - Fuel Mass Fraction Evaporated during Ignit. Delay
   63.200     - Phi_z    - Combustion duration, deg.
   1.7330     - Rs_tdc   - Swirl Ratio in the Combustion Chamber at TDC
  0.83672     - Rs_ivc   - Swirl Ratio in the Cylinder at IVC
   11.482     - W_swirl  - Max. Air Swirl Velocity, m/s  at cylinder R=   34

   ----------------------- ECOLOGICAL PARAMETERS ----------------------
   4.1772     - Hartridge- Hartridge Smoke Level
  0.45750     - Bosch    - Bosch Smoke Number
  0.09946     - K,m-1    - Factor of Absolute Light Absorption, 1/m
  0.07565     - PM       - Specific Particulate Matter, g/kWh
```

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   710.52     - CO2      - Specific Carbon dioxide emission, g/kWh
   7.2108     - NO,g/kWh - Specif. NOx emiss. reduc. to NO, g/kWh    (Zeldovich)
   1.2823     - SE       - Summary emission of PM and NOx
   0.0000     - SO2      - Specific SO2 emission, g/kWh

   ------------------------- CYLINDER PARAMETERS -----------------------
   3.0094     - p_ivc    - Pressure at IVC, bar
   386.40     - T_ivc    - Temperature at IVC, K
   123.97     - p_tdc    - Compression Pressure (at TDC), bar
   1038.6     - T_tdc    - Compression Temperature (at TDC), K
   10.518     - p_evo    - Pressure at EVO, bar
   1135.2     - T_evo    - Temperaure at EVO, K

   ------------------ HEAT EXCHANGE IN THE CYLINDER --------------------
   1064.6     - T_eq     - Average Equivalent Temperature of Cycle, K
   638.94     - hc_c     - Aver. Factor of Heat Transfer in Cyl., Wt/m2/K
   569.56     - Tw_pist  - Average Piston Crown Temperature, K
   420.00     - Tw_liner - Average Cylinder Liner Temperature, K
   517.79     - Tw_head  - Average Head Wall Temperature, K
   388.52     - Tw_cool  - Average Temperature of Cooled Surface
                 head      of Cylinder Head, K
   398.16     - Tboil    - Boiling Temp. in Liquid Cooling System, K
   12056.     - hc_cool  - Average Factor of Heat Transfer, W/(m2*K)
                           from head cooled surface to coolant
   3083.3     - q_head   - Heat Flow in a Cylinder Head, J/s
   2791.4     - q_pist   - Heat Flow in a Piston Crown, J/s
   3514.7     - q_liner  - Heat Flow in a Cylinder Liner, J/s

   --------------- MAIN ENGINE CONSTRUCTION PARAMETERS -----------------
   17.000     - CR       - Compression Ratio
   7.0000     - n_inj    - Number of Injector Nozzles
  0.17000     - d_inj    - Injector Nozzles Bore, mm
   27.000     - Phi_inj  - Injection Duration for spec. Injection Profile, deg.
   0.0000     - m_f_ip   - Fuel Mass for specified Injection Profile, g
   64.000     - EVO      - Exhaust Valve Opening, deg. before BDC
   15.000     - EVC      - Exhaust Valve Closing, deg. after  DC
   10.000     - IVO      - Intake Valve Opening, deg. before DC
   42.000     - IVC      - Intake Valve Closing, deg. after BDC

   ----------------- COMPRESSOR PARAMETERS  HP stage -------------------
   27.763     - P_C.hp   - Power of HPC, kW
  0.70700     - Eta_C.hp - Adiabatic Efficiency of HPC
  0.20620     - m_C.hp   - Mass Airflow of HP Compressor, kg/s
   3.6139     - m*_C.hp  - Mass Airflow Parameter, kg SQRT(K)/(s bar)
  0.20935     - m.cor_Chp- Corrected Mass Airflow of HPC, kg/s
   2.6500     - PR_C.hp  - Pressure Ratio of HP Compressor
  0.98000     - po_iC.hp - Inlet Total Pressure of HPC, bar
   295.00     - To_iC.hp - Inlet Total Temperature of HPC, K
   2.5970     - po_"C.hp - Total Discharge Press. (before HP cooler), bar
   428.97     - To_"C.hp - Total Discharge Temp. (before HP cooler), K
  0.75000     - Ecool.hp - Thermal Efficiency of HP Air Inter-cooler
   295.00     - Tcool.hp - HP Inter-cooler Refrigerant Temperature, K
   2.5470     - po_C.hp  - Total Pressure after Inter-cooler, bar
   328.49     - To_C.hp  - Total Temperature after Inter-cooler, ]

   ----------------- TURBINE PARAMETERS  HP stage ----------------------
   27.763     - P_T.hp   - Effective Power of HPT, kW
  0.74524     - Eta_T.hp - Internal turbine Efficiency of HPT
  0.93000     - Eta_mT.hp- Mechanical Efficiency of HPT
  0.21042     - m_T.hp   - Mass Gasflow of HPT, kg/s
   2.3190     - m*_T.hp  - Mass Gasflow Parameter, kg SQRT(K)/s kPa
   2.5081     - PR_T.hp  - Expansion Pressure Ratio of HPT
   2.6091     - po_T.hp  - Inlet Total Pressure of HPT, bar
   826.81     - To_T.hp  - Inlet Total Temperature of HPT, K
   1.0403     - po_eT.hp - HP Turbine Exhaust Back Pressure, bar
   697.53     - To_eT.hp - HP Turbine Exhaust Back Temperature, K

      THE ALLOCATION OF FUEL IN THE ZONES AT THE END OF INJECTION
========================================================================
N¦In plan¦ Spray¦Impingment¦______Fractions of fuel in the zones  %_____
s¦ Angle ¦ Angle¦ Surface  ¦ Dilut. S.Core  Piston  Inters.  Head  Liner
------------------------------------------------------------------------
1¦   0.0 ¦ 70.0 ¦pist. bowl¦ 81.75   0.71   17.54    7.56    0.00   0.00
------------------------------------------------------------------------
Sum of all sprays    % 100.¦ 66.62   2.00   11.24   20.13    0.00   0.00
========================================================================
Evaporation constants  bi  ¦  9408   5094    1014     857     686     18
========================================================================
The note: "Inters." is column with fraction of fuel in a zone of
          intersection of Near-Wall Flows formed by adjacents sprays.
Rs:Swirl¦ (Piston clearance,mm  1.00) ¦Optimal¦-Geometric formula: 1.89
   Ratio¦  Rs of piston bowl     1.73 ¦   Rs  ¦-by Razleytsev    : 1.89
```

Appendix 1 (cont.)

Engine characteristics at maximum torque regime

```
2017-02-14 17-50-23 "JCB-129"
Mode: #3  : Max torque 690 Nm;
Fuel:      Diesel No. 2

   ----------------- PARAMETERS OF EFFICIENCY AND POWER ----------------
   1500.0     - RPM      - Engine Speed, rev/min
   108.90     - P_eng    - Piston Engine Power, kW
   18.282     - BMEP     - Brake Mean Effective Pressure, bar
   693.32     - Torque   - Brake Torque, N m
  0.12850     - m_f      - Mass of Fuel Supplied per cycle, g
  0.21240     - SFC      - Specific Fuel Consumption, kg/kWh
  0.39880     - Eta_f    - Efficiency of piston engine
   20.518     - IMEP     - Indicated Mean Effective Pressure, bar
  0.44758     - Eta_i    - Indicated Efficiency
   2.3178     - FMEP     - Friction Mean Effective Pressure, bar
  0.89103     - Eta_m    - Mechanical Efficiency of Piston Engine

   --------------------- ENVIRONMENTAL PARAMETERS ----------------------
   1.0000     - po_amb   - Total Ambient Pressure, bar
   295.00     - To_amb   - Total Ambient Temperature, K
   1.0200     - p_Te     - Exhaust Back Pressure, bar (after turbine)
  0.99000     - po_afltr - Total Pressure after Induction Air Filter, bar

   ------------------ TURBOCHARGING AND GAS EXCHANGE -------------------
   2.3260     - p_C      - Pressure before Inlet Manifold, bar
   324.65     - T_C      - Temperature before Inlet Manifold, K
  0.13881     - m_air    - Total Mass Airflow (+EGR) of Piston Engine, kg/s
  0.50896     - Eta_TC   - Turbocharger Efficiency
   2.1238     - po_T     - Average Total Turbine Inlet Pressure, bar
   863.29     - To_T     - Average Total Turbine Inlet Temperature, K
  0.14175     - m_gas    - Mass Exhaust Gasflow of Pison Engine, [g/s
   1.4907     - A/F_eq.t - Total Air Fuel Equivalence Ratio
  0.67082     - F/A_eq.t - Total Fuel Air Equivalence Ratio
  0.08203     - PMEP     - Pumping Mean Effective Pressure, bar
  0.94243     - Eta_v    - Volumetric Efficiency
  0.02946     - x_r      - Residual Gas Mass Fraction
  0.99092     - Phi      - Coeff. of Scavenging (Delivery Ratio / Eta_v)
  0.05016     - BF_int   - Burnt Gas Fraction Backflowed into the Intake, %
   2.4690     - %Blow-by - % of Blow-by through piston rings

   -------------------------- INTAKE SYSTEM ---------------------------
   2.3188     - p_int    - Average Intake Manifold Pressure, bar
   326.33     - T_int    - Average Intake Manifold Temperature, K
   329.33     - Tw_int   - Average Intake Manifold Wall Temperature, K
   110.01     - hc_int   - Heat Transfer Coeff. in Intake Manifold, W/(m2*K)
   222.76     - hc_int.p - Heat Transfer Coeff. in Intake Port, W/(m2*K)

   -------------------------- EXHAUST SYSTEM ---------------------------
   2.1181     - p_exh    - Average Exhaust Manifold Gas Pressure, bar
   862.72     - T_exh    - Average Exhaust Manifold Gas Temperature, K
   39.870     - v_exh    - Average Gas Velocity in exhaust manifold, m/s
   19.873     - Sh       - Strouhal number: Sh=a*Tau/L (has to be: Sh > 8)
   762.02     - Tw_exh   - Average Exhaust Manifold Wall Temperature, K
   111.51     - hc_exh   - Heat Transfer Coeff. in Exhaust Manifold, W/(m2*K)
   919.74     - hc_exh.p - Heat Transfer Coeff. in Exhaust Port, W/(m2*K)

   ---------------------------- COMBUSTION -----------------------------
   1.5047     - A/F_eq   - Air Fiel Equivalence Ratio in the Cylinder
  0.66460     - F/A_eq   - Fuel Air Equivalence Ratio in the Cylinder
   167.26     - p_max    - Maximum Cylinder Pressure, bar
   2017.7     - T_max    - Maximum Cylinder Temperature, K
   7.0000     - CA_p.max - Angle of Max. Cylinder Pressure, deg. A.TDC
   24.000     - CA_t.max - Angle of Max. Cylinder Temperature, deg. A.TDC
   11.229     - dp/dTheta- Max. Rate of Pressure Rise, bar/deg.
  Injection: Custom Fuel Injection System
   1660.0     - p_inj.max- Max. Injection Pres. (before nozzles), bar
   9.4600     - d_32     - Sauter Mean Diameter of Drops, microns
   8.0000     - Theta_i  - Injection / Ignition Timing, deg. B.TDC
   22.039     - Phi_inj  - Duration of Injection, deg.
   3.0880     - Phi_id   - Ignition Delay Period, deg.
  0.05293     - x_e.id   - Fuel Mass Fraction Evaporated during Ignit. Delay
   70.200     - Phi_z    - Combustion duration, deg.
   1.7330     - Rs_tdc   - Swirl Ratio in the Combustion Chamber at TDC
  0.80798     - Rs_ivc   - Swirl Ratio in the Cylinder at IVC
   8.4018     - W_swirl  - Max. Air Swirl Velocity, m/s  at cylinder R=   34

   ------------------------ ECOLOGICAL PARAMETERS ----------------------
   4.6130     - Hartridge- Hartridge Smoke Level
  0.50543     - Bosch    - Bosch Smoke Number
  0.11032     - K,m-1    - Factor of Absolute Light Absorption, 1/m
```

```
  0.06873     - PM       - Specific Particulate Matter, g/kWh
   684.40     - CO2      - Specific Carbon dioxide emission, g/kWh
  0.81736     - NO,g/kWh - Specif. NOx emiss. reduc. to NO, g/kWh    (Zeldovich)
```

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  0.34588     - SE       - Summary emission of PM and NOx
   0.0000     - SO2      - Specific SO2 emission, g/kWh

   ------------------------- CYLINDER PARAMETERS -----------------------
   2.6888     - p_ivc    - Pressure at IVC, bar
   376.29     - T_ivc    - Temperature at IVC, K
   111.00     - p_tdc    - Compression Pressure (at TDC), bar
   1015.7     - T_tdc    - Compression Temperature (at TDC), K
   10.360     - p_evo    - Pressure at EVO, bar
   1214.8     - T_evo    - Temperaure at EVO, K

   ------------------ HEAT EXCHANGE IN THE CYLINDER --------------------
   1210.5     - T_eq     - Average Equivalent Temperature of Cycle, K
   525.95     - hc_c     - Aver. Factor of Heat Transfer in Cyl., Wt/m2/K
   575.73     - Tw_pist  - Average Piston Crown Temperature, K
   420.00     - Tw_liner - Average Cylinder Liner Temperature, K
   523.45     - Tw_head  - Average Head Wall Temperature, K
   390.72     - Tw_cool  - Average Temperature of Cooled Surface
                 head      of Cylinder Head, K
   398.16     - Tboil    - Boiling Temp. in Liquid Cooling System, K
   11946.     - hc_cool  - Average Factor of Heat Transfer, W/(m2*K)
                           from head cooled surface to coolant
   3188.6     - q_head   - Heat Flow in a Cylinder Head, J/s
   2946.0     - q_pist   - Heat Flow in a Piston Crown, J/s
   2921.3     - q_liner  - Heat Flow in a Cylinder Liner, J/s

   --------------- MAIN ENGINE CONSTRUCTION PARAMETERS -----------------
   17.000     - CR       - Compression Ratio
   7.0000     - n_inj    - Number of Injector Nozzles
  0.17000     - d_inj    - Injector Nozzles Bore, mm
   22.000     - Phi_inj  - Injection Duration for spec. Injection Profile, deg.
   0.0000     - m_f_ip   - Fuel Mass for specified Injection Profile, g
   64.000     - EVO      - Exhaust Valve Opening, deg. before BDC
   15.000     - EVC      - Exhaust Valve Closing, deg. after  DC
   10.000     - IVO      - Intake Valve Opening, deg. before DC
   42.000     - IVC      - Intake Valve Closing, deg. after BDC

   ----------------- COMPRESSOR PARAMETERS  HP stage -------------------
   16.543     - P_C.hp   - Power of HPC, kW
  0.70700     - Eta_C.hp - Adiabatic Efficiency of HPC
  0.13881     - m_C.hp   - Mass Airflow of HP Compressor, kg/s
   2.4082     - m*_C.hp  - Mass Airflow Parameter, kg SQRT(K)/(s bar)
  0.13951     - m.cor_Chp- Corrected Mass Airflow of HPC, kg/s
   2.4000     - PR_C.hp  - Pressure Ratio of HP Compressor
  0.99000     - po_iC.hp - Inlet Total Pressure of HPC, bar
   295.00     - To_iC.hp - Inlet Total Temperature of HPC, K
   2.3760     - po_"C.hp - Total Discharge Press. (before HP cooler), bar
   413.58     - To_"C.hp - Total Discharge Temp. (before HP cooler), K
  0.75000     - Ecool.hp - Thermal Efficiency of HP Air Inter-cooler
   295.00     - Tcool.hp - HP Inter-cooler Refrigerant Temperature, K
   2.3260     - po_C.hp  - Total Pressure after Inter-cooler, bar
   324.65     - To_C.hp  - Total Temperature after Inter-cooler, ]

   ----------------- TURBINE PARAMETERS  HP stage ----------------------
   16.572     - P_T.hp   - Effective Power of HPT, kW
  0.77565     - Eta_T.hp - Internal turbine Efficiency of HPT
  0.93000     - Eta_mT.hp- Mechanical Efficiency of HPT
  0.14175     - m_T.hp   - Mass Gasflow of HPT, kg/s
   1.9611     - m*_T.hp  - Mass Gasflow Parameter, kg SQRT(K)/s kPa
   2.0817     - PR_T.hp  - Expansion Pressure Ratio of HPT
   2.1238     - po_T.hp  - Inlet Total Pressure of HPT, bar
   863.29     - To_T.hp  - Inlet Total Temperature of HPT, K
   1.0202     - po_eT.hp - HP Turbine Exhaust Back Pressure, bar
   749.68     - To_eT.hp - HP Turbine Exhaust Back Temperature, K

      THE ALLOCATION OF FUEL IN THE ZONES AT THE END OF INJECTION
=====================================================================
N¦In plan¦ Spray¦Impingment¦______Fractions of fuel in the zones  %_____
s¦ Angle ¦ Angle¦ Surface  ¦ Dilut. S.Core  Piston  Inters.  Head  Liner
---------------------------------------------------------------------
1¦   0.0 ¦ 70.0 ¦pist. bowl¦ 79.06   0.00   20.37   14.97    0.57   0.00
---------------------------------------------------------------------
Sum of all sprays    % 100.¦ 63.97   2.84    6.45   26.15    0.59   0.00
=====================================================================
Evaporation constants  bi  ¦ 14498   8692    1592    1345    1076     27
=====================================================================
The note: "Inters." is column with fraction of fuel in a zone of
          intersection of Near-Wall Flows formed by adjacents sprays.
```

```
Rs:Swirl¦ (Piston clearance,mm  1.00) ¦Optimal¦-Geometric formula: 2.33
   Ratio¦  Rs of piston bowl     1.73 ¦   Rs  ¦-by Razleytsev    : 2.08
```

Appendix 1 (cont.)

2017-02-13 22-32-15 "JCB-129" Engine characteristics at idling regime

```
Mode: #5  : Idling;
Fuel:      Diesel No. 2

   ----------------- PARAMETERS OF EFFICIENCY AND POWER ----------------
   850.00     - RPM       - Engine Speed, rev/min
   2.9445     - P_eng     - Piston Engine Power, kW
  0.87232     - BMEP      - Brake Mean Effective Pressure, bar
   33.082     - Torque    - Brake Torque, N m
  0.01300     - m_f       - Mass of Fuel Supplied per cycle, g
  0.45034     - SFC       - Specific Fuel Consumption, kg/kWh
  0.18809     - Eta_f     - Efficiency of piston engine
   1.8991     - IMEP      - Indicated Mean Effective Pressure, bar
  0.40949     - Eta_i     - Indicated Efficiency
  0.89655     - FMEP      - Friction Mean Effective Pressure, bar
  0.45934     - Eta_m     - Mechanical Efficiency of Piston Engine

   --------------------- ENVIRONMENTAL PARAMETERS ----------------------
   1.0000     - po_amb    - Total Ambient Pressure, bar
   295.00     - To_amb    - Total Ambient Temperature, K
   1.0040     - p_Te      - Exhaust Back Pressure, bar (after turbine)
  0.99800     - po_afltr - Total Pressure after Induction Air Filter, bar

   ------------------ TURBOCHARGING AND GAS EXCHANGE -------------------
  0.95798     - p_C       - Pressure before Inlet Manifold, bar
   295.48     - T_C       - Temperature before Inlet Manifold, K
  0.03500     - m_air     - Total Mass Airflow (+EGR) of Piston Engine, kg/s
  0.20096     - Eta_TC    - Turbocharger Efficiency
   1.0432     - po_T      - Average Total Turbine Inlet Pressure, bar
   405.28     - To_T      - Average Total Turbine Inlet Temperature, K
  0.03402     - m_gas     - Mass Exhaust Gasflow of Pison Engine, [g/s
   6.5565     - A/F_eq.t - Total Air Fuel Equivalence Ratio
  0.15252     - F/A_eq.t - Total Fuel Air Equivalence Ratio
 -0.13019     - PMEP      - Pumping Mean Effective Pressure, bar
  0.96141     - Eta_v     - Volumetric Efficiency
  0.05280     - x_r       - Residual Gas Mass Fraction
  0.95507     - Phi       - Coeff. of Scavenging (Delivery Ratio / Eta_v)
  0.38266     - BF_int    - Burnt Gas Fraction Backflowed into the Intake, %
   3.4743     - %Blow-by - % of Blow-by through piston rings

   --------------------------- INTAKE SYSTEM ---------------------------
  0.95682     - p_int     - Average Intake Manifold Pressure, bar
   297.68     - T_int     - Average Intake Manifold Temperature, K
   300.68     - Tw_int    - Average Intake Manifold Wall Temperature, K
   65.679     - hc_int    - Heat Transfer Coeff. in Intake Manifold, W/(m2*K)
   149.44     - hc_int.p - Heat Transfer Coeff. in Intake Port, W/(m2*K)

   -------------------------- EXHAUST SYSTEM ---------------------------
   1.0429     - p_exh     - Average Exhaust Manifold Gas Pressure, bar
   405.25     - T_exh     - Average Exhaust Manifold Gas Temperature, K
   9.2060     - v_exh     - Average Gas Velocity in exhaust manifold, m/s
   24.036     - Sh        - Strouhal number: Sh=a*Tau/L (has to be: Sh > 8)
   388.32     - Tw_exh    - Average Exhaust Manifold Wall Temperature, K
   90.000     - hc_exh    - Heat Transfer Coeff. in Exhaust Manifold, W/(m2*K)
   446.80     - hc_exh.p - Heat Transfer Coeff. in Exhaust Port, W/(m2*K)

   ---------------------------- COMBUSTION -----------------------------
   6.8653     - A/F_eq    - Air Fiel Equivalence Ratio in the Cylinder
  0.14566     - F/A_eq    - Fuel Air Equivalence Ratio in the Cylinder
   62.593     - p_max     - Maximum Cylinder Pressure, bar
   1284.4     - T_max     - Maximum Cylinder Temperature, K
   3.0000     - CA_p.max - Angle of Max. Cylinder Pressure, deg. A.TDC
   5.0000     - CA_t.max - Angle of Max. Cylinder Temperature, deg. A.TDC
   6.9935     - dp/dTheta- Max. Rate of Pressure Rise, bar/deg.
  Injection: Custom Fuel Injection System
   517.01     - p_inj.max- Max. Injection Pres. (before nozzles), bar
   19.109     - d_32      - Sauter Mean Diameter of Drops, microns
   10.000     - Theta_i   - Injection / Ignition Timing, deg. B.TDC
   3.0000     - Phi_inj   - Duration of Injection, deg.
   4.8225     - Phi_id    - Ignition Delay Period, deg.
  0.63601     - x_e.id    - Fuel Mass Fraction Evaporated during Ignit. Delay
   19.800     - Phi_z     - Combustion duration, deg.
   1.7330     - Rs_tdc    - Swirl Ratio in the Combustion Chamber at TDC
  0.80080     - Rs_ivc    - Swirl Ratio in the Cylinder at IVC
```

```
  4.7610     - W_swirl  - Max. Air Swirl Velocity, m/s  at cylinder R=   34

  ------------------------- ECOLOGICAL PARAMETERS ----------------------
  16.896     - Hartridge- Hartridge Smoke Level
  1.7307     - Bosch    - Bosch Smoke Number
 0.43572     - K,m-1    - Factor of Absolute Light Absorption, 1/m
  2.9211     - PM       - Specific Particulate Matter, g/kWh
  1451.1     - CO2      - Specific Carbon dioxide emission, g/kWh
  20.478     - NO,g/kWh - Specif. NOx emiss. reduc. to NO, g/kWh    (Zeldovich)
```

Приложение 1

```
  12.662     - SE       - Summary emission of PM and NOx
  0.0000     - SO2      - Specific SO2 emission, g/kWh

  ------------------------- CYLINDER PARAMETERS -----------------------
  1.0898     - p_ivc    - Pressure at IVC, bar
  334.12     - T_ivc    - Temperature at IVC, K
  45.030     - p_tdc    - Compression Pressure (at TDC), bar
  907.69     - T_tdc    - Compression Temperature (at TDC), K
  1.8203     - p_evo    - Pressure at EVO, bar
  493.92     - T_evo    - Temperaure at EVO, K

  ------------------ HEAT EXCHANGE IN THE CYLINDER --------------------
  717.97     - T_eq     - Average Equivalent Temperature of Cycle, K
  157.20     - hc_c     - Aver. Factor of Heat Transfer in Cyl., Wt/m2/K
  426.42     - Tw_pist  - Average Piston Crown Temperature, K
  420.00     - Tw_liner - Average Cylinder Liner Temperature, K
  387.73     - Tw_head  - Average Head Wall Temperature, K
  368.97     - Tw_cool  - Average Temperature of Cooled Surface
                  head    of Cylinder Head, K
  398.16     - Tboil    - Boiling Temp. in Liquid Cooling System, K
  6042.5     - hc_cool  - Average Factor of Heat Transfer, W/(m2*K)
                          from head cooled surface to coolant
  458.11     - q_head   - Heat Flow in a Cylinder Head, J/s
  404.43     - q_pist   - Heat Flow in a Piston Crown, J/s
  12.463     - q_liner  - Heat Flow in a Cylinder Liner, J/s

  --------------- MAIN ENGINE CONSTRUCTION PARAMETERS -----------------
  17.000     - CR       - Compression Ratio
  7.0000     - n_inj    - Number of Injector Nozzles
 0.17000     - d_inj    - Injector Nozzles Bore, mm
  3.0000     - Phi_inj  - Injection Duration for spec. Injection Profile, deg.
  0.0000     - m_f_ip   - Fuel Mass for specified Injection Profile, g
  64.000     - EVO      - Exhaust Valve Opening, deg. before BDC
  15.000     - EVC      - Exhaust Valve Closing, deg. after  DC
  10.000     - IVO      - Intake Valve Opening, deg. before DC
  42.000     - IVC      - Intake Valve Closing, deg. after BDC

  ----------------- COMPRESSOR PARAMETERS  HP stage -------------------
 0.06714     - P_C.hp   - Power of HPC, kW
 0.44000     - Eta_C.hp - Adiabatic Efficiency of HPC
 0.03500     - m_C.hp   - Mass Airflow of HP Compressor, kg/s
 0.60236     - m*_C.hp  - Mass Airflow Parameter, kg SQRT(K)/(s bar)
 0.03489     - m.cor_Chp- Corrected Mass Airflow of HPC, kg/s
  1.0100     - PR_C.hp  - Pressure Ratio of HP Compressor
 0.99800     - po_iC.hp - Inlet Total Pressure of HPC, bar
  295.00     - To_iC.hp - Inlet Total Temperature of HPC, K
  1.0080     - po_"C.hp - Total Discharge Press. (before HP cooler), bar
  296.91     - To_"C.hp - Total Discharge Temp. (before HP cooler), K
 0.75000     - Ecool.hp - Thermal Efficiency of HP Air Inter-cooler
  295.00     - Tcool.hp - HP Inter-cooler Refrigerant Temperature, K
 0.95798     - po_C.hp  - Total Pressure after Inter-cooler, bar
  295.48     - To_C.hp  - Total Temperature after Inter-cooler, ]

  ----------------- TURBINE PARAMETERS  HP stage ----------------------
 0.06716     - P_T.hp   - Effective Power of HPT, kW
 0.48876     - Eta_T.hp - Internal turbine Efficiency of HPT
 0.93000     - Eta_mT.hp- Mechanical Efficiency of HPT
 0.03402     - m_T.hp   - Mass Gasflow of HPT, kg/s
 0.65656     - m*_T.hp  - Mass Gasflow Parameter, kg SQRT(K)/s kPa
  1.0392     - PR_T.hp  - Expansion Pressure Ratio of HPT
  1.0432     - po_T.hp  - Inlet Total Pressure of HPT, bar
  405.28     - To_T.hp  - Inlet Total Temperature of HPT, K
  1.0038     - po_eT.hp - HP Turbine Exhaust Back Pressure, bar
  403.39     - To_eT.hp - HP Turbine Exhaust Back Temperature, K

     THE ALLOCATION OF FUEL IN THE ZONES AT THE END OF INJECTION
=========================================================================
N¦In plan¦ Spray¦Impingment¦______Fractions of fuel in the zones  %_____
s¦ Angle ¦ Angle¦ Surface  ¦ Dilut. S.Core  Piston  Inters.  Head  Liner
-------------------------------------------------------------------------
1¦   0.0 ¦ 70.0 ¦pist. bowl¦ 72.80  13.72   10.04    0.00    0.00   0.00
-------------------------------------------------------------------------
```

```
Sum of all sprays    % 100.¦ 77.35  22.65    0.00    0.00    0.00   0.00
=========================================================================
Evaporation constants  bi  ¦  4365    439     353     298     323     13
=========================================================================
The note: "Inters." is column with fraction of fuel in a zone of
          intersection of Near-Wall Flows formed by adjacents sprays.
____________________
Versions:     Kernel 24.09.08;  RK-model 25.09.08;  NOx-model 5.06.08
```

Appendix 2

Application of multiple injections

Usually, in modern IC engines with common rail system and severe limitation on the maximum in-cylinder pressure, an important restriction should be set to the combustion intensity or the rate of in-cylinder pressure rise *dp/dΘ*. The dominant role of this restriction is due to a sharp increase in the fuel supply rate (the fuel injection profile for common rail system is close to rectangular). The most relevant and important this restriction becomes at the maximum torque regime and further with the decreasing RPM, as shown in Figure 16, graph *dp/dTheta*.

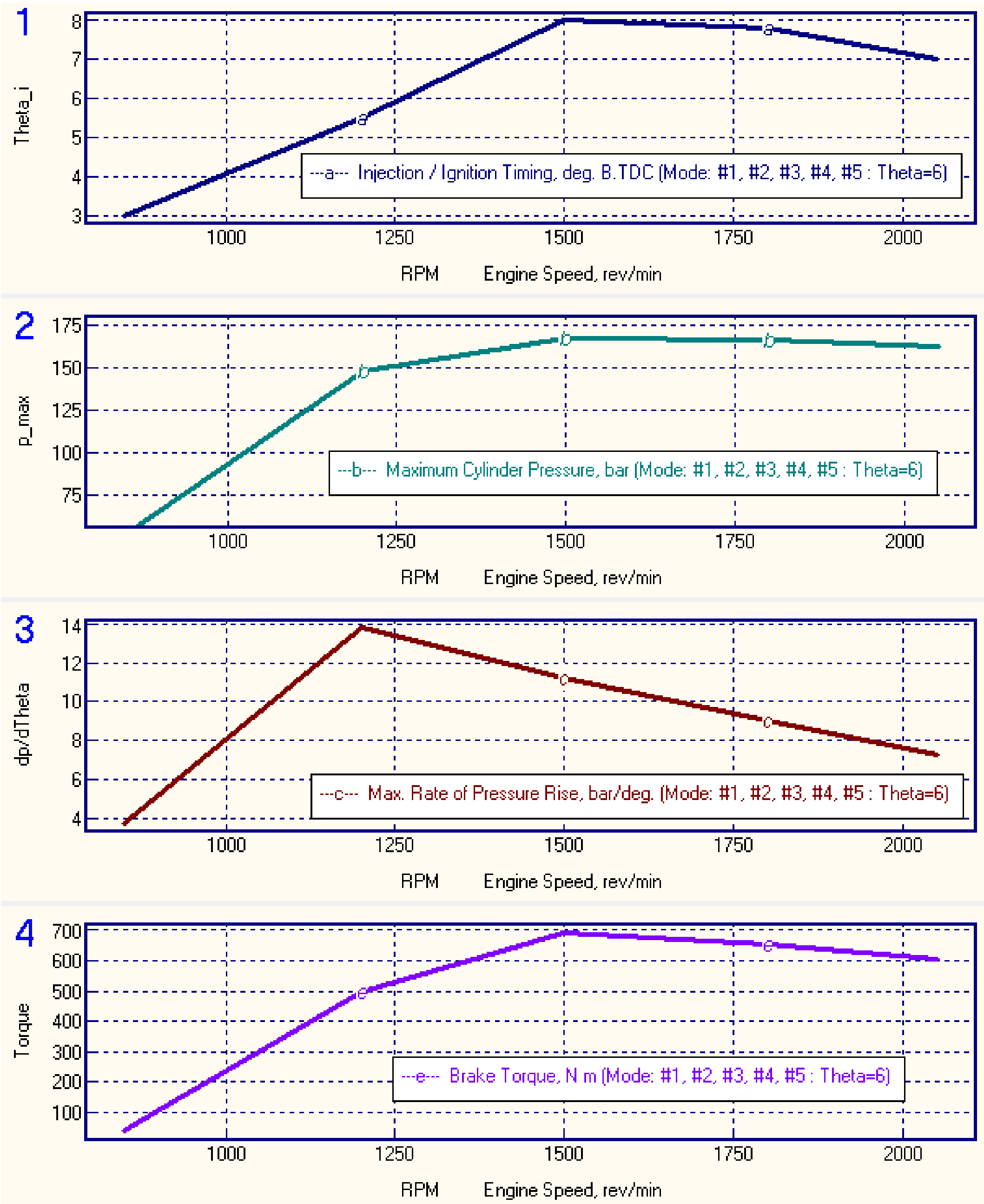
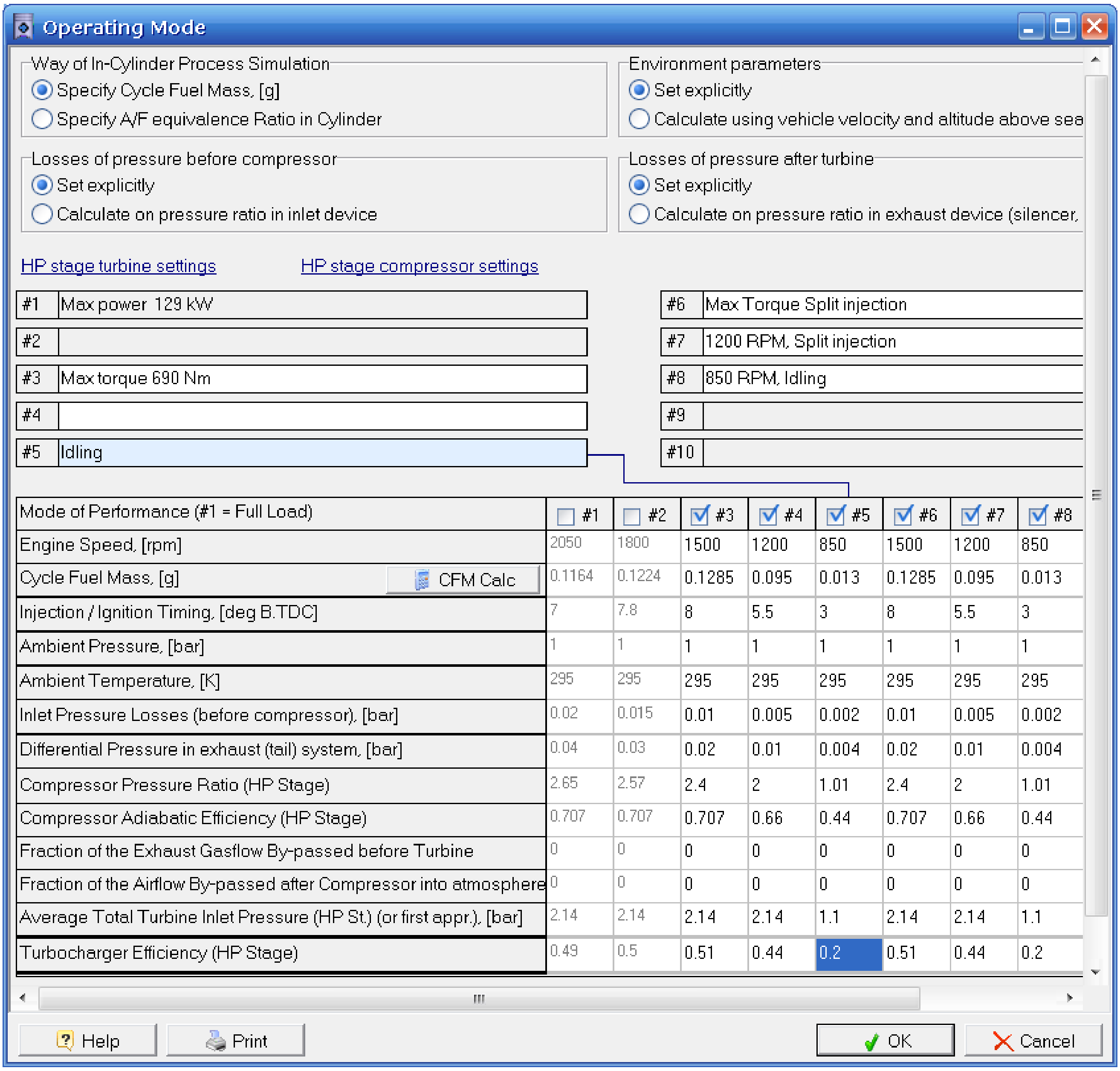


Figure 16. The change of the following engine parameters vs. RPM: (a) Fuel injection timing *Theta_i* [deg. BTDC], (b) Maximum cylinder pressure *p_max* [bar], (c) The rate of pressure rise *dp/dTheta* [bar/degree], (d) Torque *Torque* [Nm].

To reduce the rate of pressure rise, small amount of pilot fuel injection can be applied. It can be easily implemented with the common rail system. In this example, the pilot fuel injection at regimes of 1500 RPM and 1200 RPM will be implemented.

Step 14 Selection of the alternative regimes with multiple injections

To set additional regimes for the engine output characteristics, select the columns with regimes No. 3, 4, 5, 6, 7 and transfer the data from column # 3 to column # 6; and from column No. 4 to column No. 7 (Figure 17).



Mode of Performance (#1 = Full Load)	#1	#2	#3	#4	#5	#6	#7	#8
Engine Speed, [rpm]	2050	1800	1500	1200	850	1500	1200	850
Cycle Fuel Mass, [g]	0.1164	0.1224	0.1285	0.095	0.013	0.1285	0.095	0.013
Injection / Ignition Timing, [deg B.TDC]	7	7.8	8	5.5	3	8	5.5	3
Ambient Pressure, [bar]	1	1	1	1	1	1	1	1
Ambient Temperature, [K]	295	295	295	295	295	295	295	295
Inlet Pressure Losses (before compressor), [bar]	0.02	0.015	0.01	0.005	0.002	0.01	0.005	0.002
Differential Pressure in exhaust (tail) system, [bar]	0.04	0.03	0.02	0.01	0.004	0.02	0.01	0.004
Compressor Pressure Ratio (HP Stage)	2.65	2.57	2.4	2	1.01	2.4	2	1.01
Compressor Adiabatic Efficiency (HP Stage)	0.707	0.707	0.707	0.66	0.44	0.707	0.66	0.44
Fraction of the Exhaust Gasflow By-passed before Turbine	0	0	0	0	0	0	0	0
Fraction of the Airflow By-passed after Compressor into atmosphere	0	0	0	0	0	0	0	0
Average Total Turbine Inlet Pressure (HP St.) (or first appr.), [bar]	2.14	2.14	2.14	2.14	1.1	2.14	2.14	1.1
Turbocharger Efficiency (HP Stage)	0.49	0.5	0.51	0.44	0.2	0.51	0.44	0.2

Figure 17. Selection of additional regimes No. 6, and 7 for the engine output characteristics.

It is convenient to set the injection characteristics with the pilot injection for common rail system parametrically. To set this, select **Parametric** under the **Way of Injection Profile Specification** as shown in Figure 18. For regimes No. 6 and 7, manually transfer the mass of injected fuel from regimes 3 and 4, respectively. Due to the fact that the multiple injection is implemented by the common rail system, the fuel pressure for modes 6, 7 should be set explicitly, as was calculated above in Figure 9, we set 1520 bar. Set for the regimes 6 and 7 two-portion injection, transferring all fuel from portion 3 to portion 2, and also a part of the fuel from portion 1 to portion 2. It is recommended to set the proportion of the pilot injection to 0.05, and the delay between portions to 3 degrees for regime No. 6 (maximum torque at 1500 RPM) as shown in Figure 18 and to 5 degrees for the regime No. 7 (lower RPM 1200 RPM) as shown in Figure 19.

Injection Velocity Increase/Decrease duration [deg.CA] is set to 2.5 deg as shown in Figure 18. In the "Options" => "Solver Settings" window, deactivate **Self learning**; this will make the calculation more stable to fluctuations in the initial conditions.

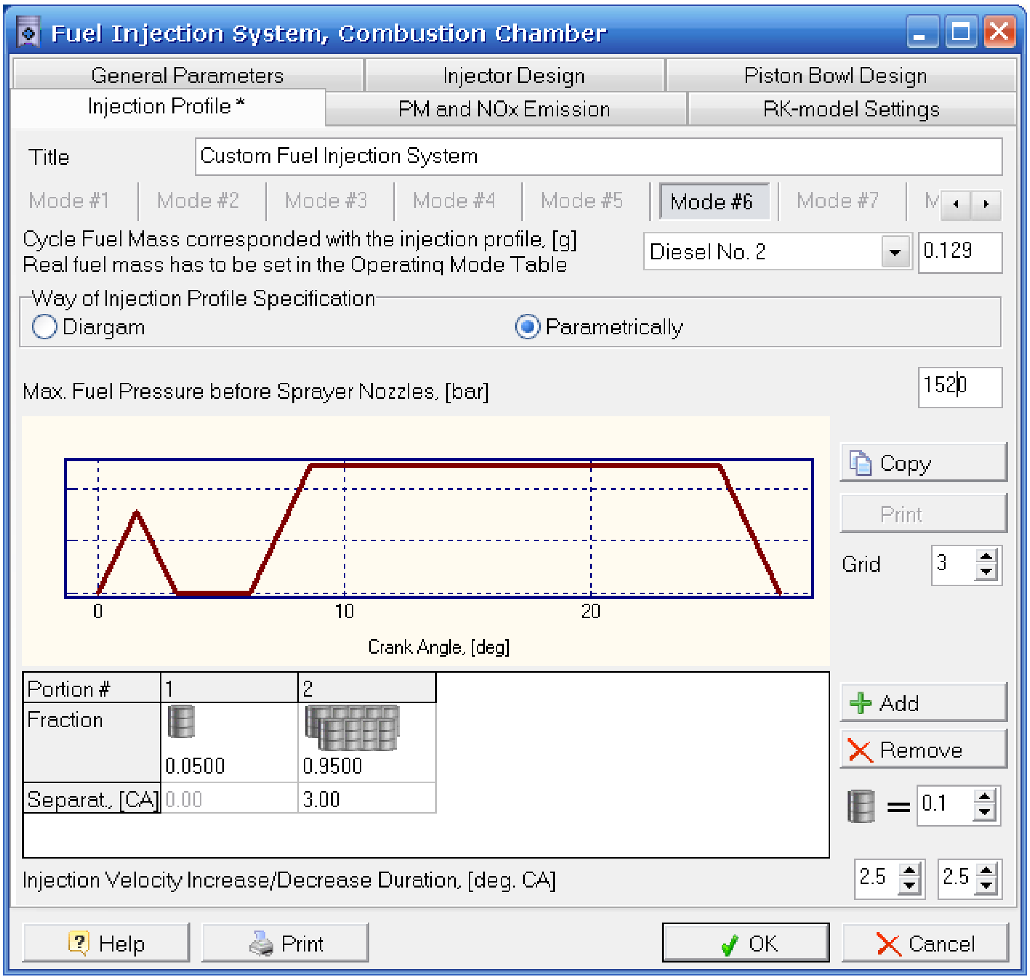


Figure 18. Settings for the injection characteristics with common rail system for regime No. 6 (maximum torque at 1500 RPM).

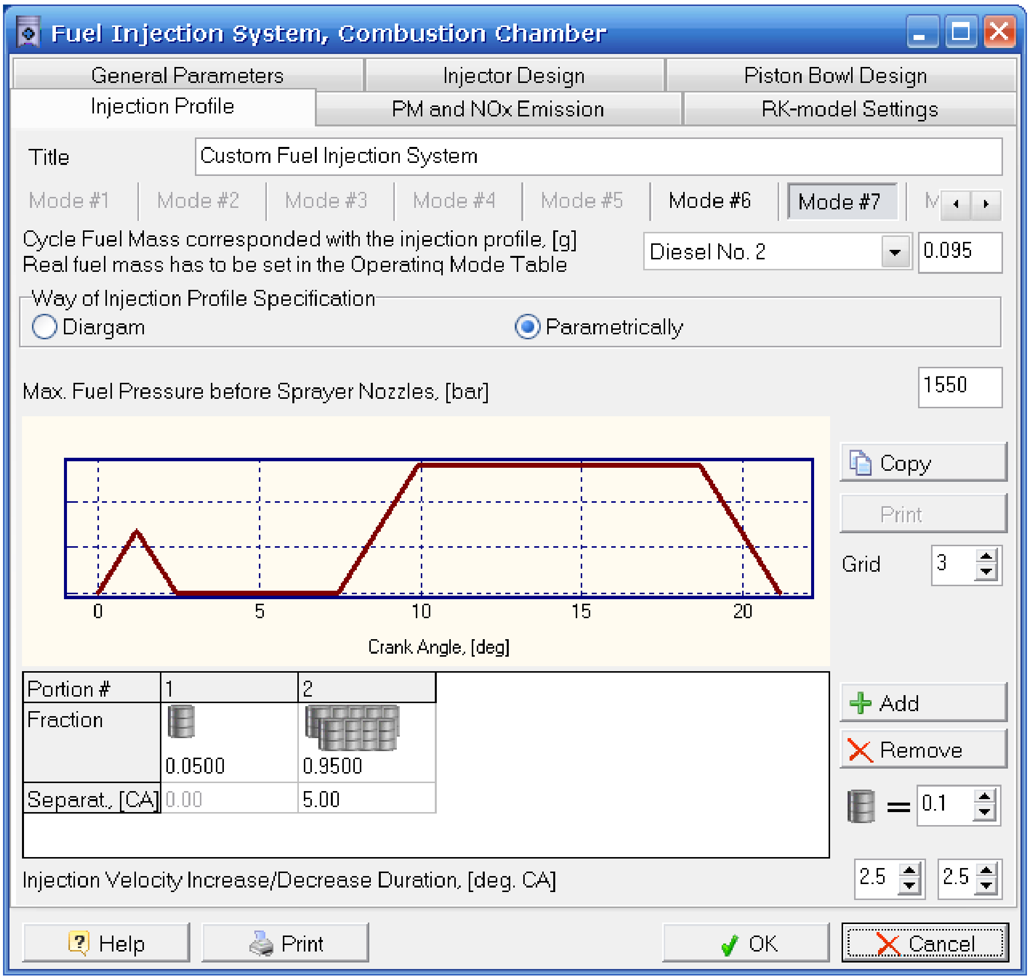


Figure 19. Settings for the injection characteristics with common rail system for regime No. 7 (lower engine speed at 1200 RPM).

Step 15 Selection of fuel multiple injection timings with high combustion intensity

In this case, the maximum rate of pressure rise *dp/dTheta* = 13.8 bar/deg. occurs at RPM = 1200. Also, the high combustion intensity occurs at maximum torque regime.
To select the optimal fuel injection timing perform a one-dimensional parametric study (scanning) using the *Theta_i* angle, as was done in Step 10 for regimes No. 6 and 7. The computed results are shown in Figure 20. From the graphs in Figure 20, you can select the optimal value of *Theta_i*.

For the maximum torque regime (1500 RPM) *Theta_i* = 10 deg BTDC is selected, in this case the rate of pressure rise does not exceed 7 bar/deg., which is obtained at maximum power regime.

For the 1200 RPM mode, *Theta_i* = 8 deg. BTDC is selected, in this case the rate of pressure rise is about 6.5 bar/deg, and the fuel consumption (SFC) is minimal. Fix the obtained values of the injection timings in the Operating Mode table. Perform computations of these modes separately to obtain engine input and output parameters, similar to those presented in Appendix 1.

The version of program No. 143 may not work reliably when performing parametric studies with pilot injection. In this case, carry out the study in manual mode, changing the injection timing and selecting its optimal value. To plot the graph presented in Figure 20 you can use Excel. Also for this step you can use newer versions of the program, for example 189 or newer.

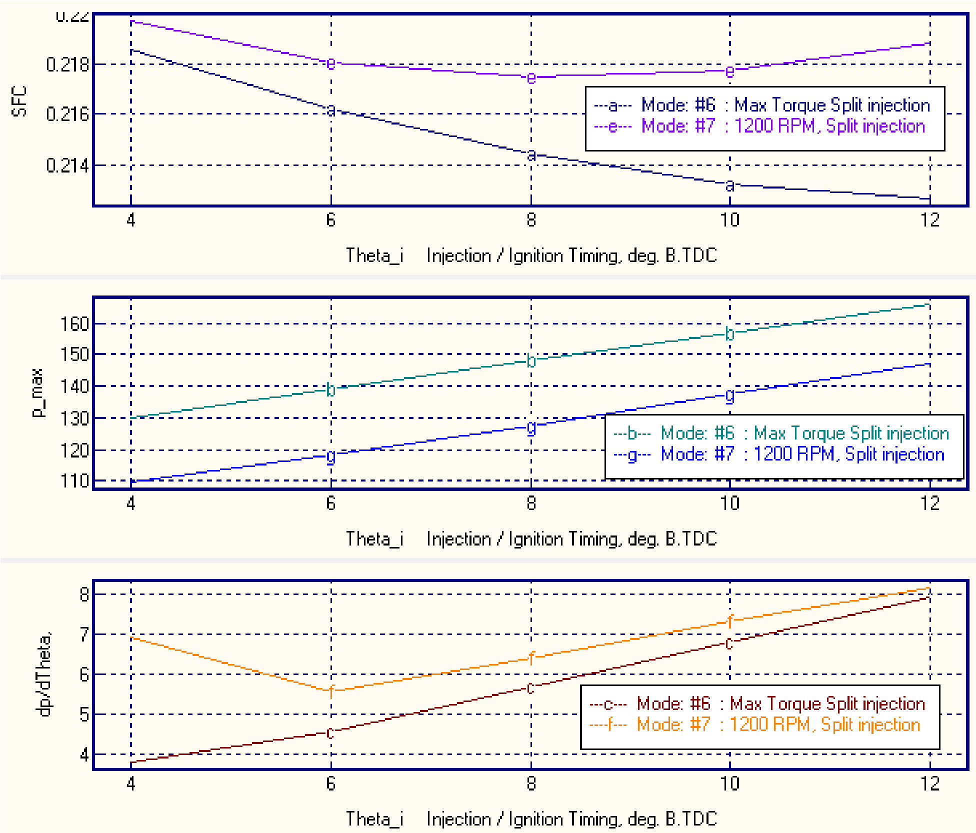


Figure 20. The effect of the injection timing *Theta_i* on engine parameters at regime No. 6 (1500 RPM) and No. 7 (1200 RPM).

Step 16 Construction of engine output characteristics for diesel engine with multiple fuel injection (the restricted combustion intensity)

Form the table in Excel program with the received parameters of each engine regime

Table 5. Engine parameters for engine output characteristics with multiple fuel injection

RPM	2050	1800	1500	1200	850
P_eng, kW	129.8	123.1	108.4	62.9	3.4
Torque, Nm	605	653	690	500	38
BMEP, bar	15.95	17.2	18.2	13.2	1.01
SFC, kg/kW h	0.2205	0.2148	0.2133	0.2175	0.389
Theta_i, CA deg.BTDC	7	7.8	10	8	3
p_max, bar	163	166.6	155.2	127.4	52.7
dp/dTheta, bar/deg.	7.28	8.9	6.42	6.39	3.8

Construct the graphs as shown in Figure 21 for the engine operating parameters versus RPM. If the combustion intensity for certain regimes is unacceptably high, apply the multiple fuel injection strategy for these modes.

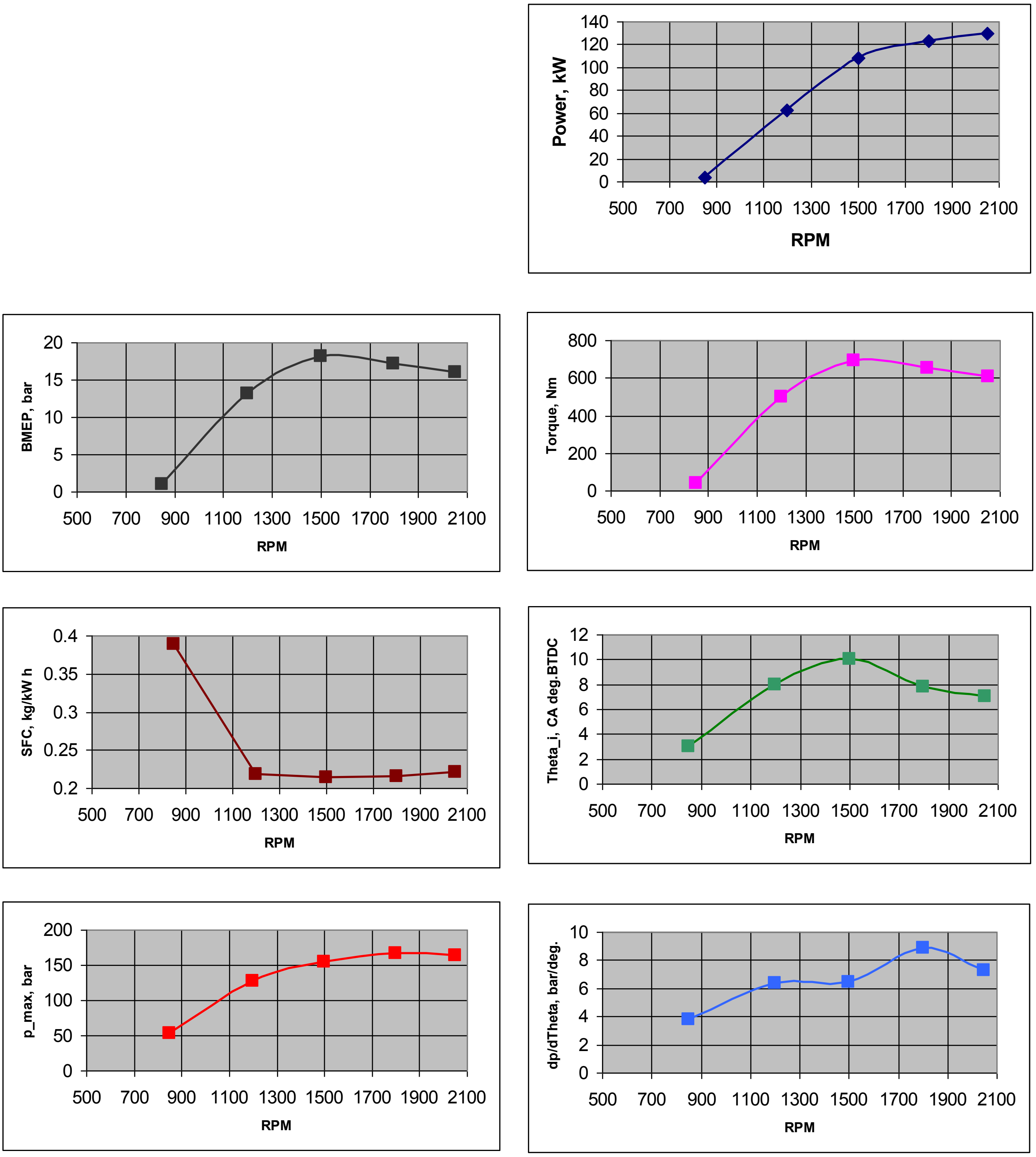


Figure 21. Engine operating parameters with fuel multiple injection for diesel output characteristics.

Step 17 Compare the rate of heat release rate and in-cylinder pressure with single and double injections at 1200 RPM.

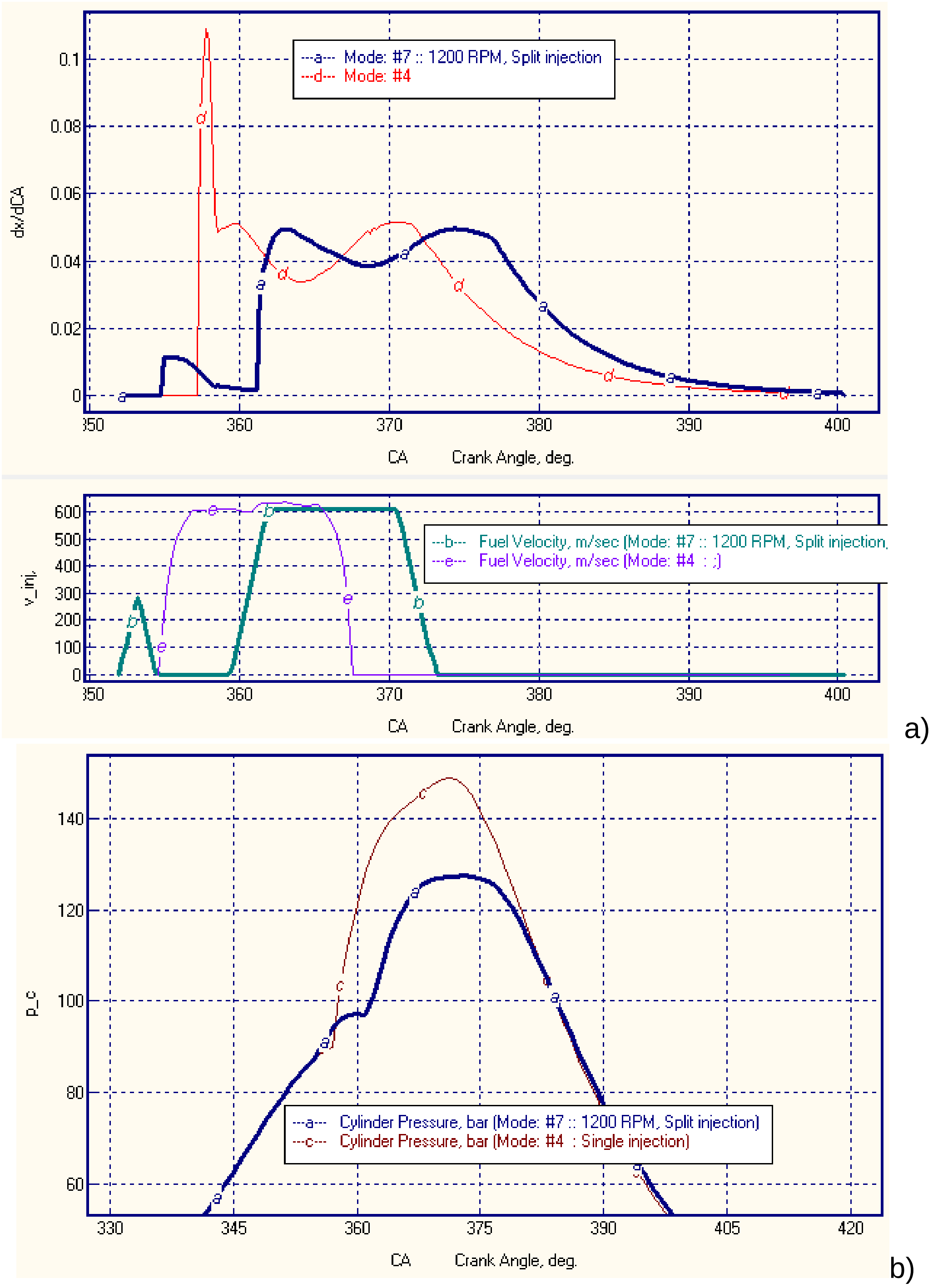


Figure 22. Comparison of (a) the rate of heat release and (b) in-cylinder pressure with single and double injections at 1200 RPM.

Pilot portion of the injected fuel provides heating of the charge and reduction of the delay period for the main portion, therefore the rate of pressure rise significantly decreases.

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