Practical Exercise:

Computation of the engine output characteristics for a 4-stroke spark ignition engine

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The main objectives of the work:
    1. To familiarize students with the advanced software in order to compute and optimize internal combustion engine parameters and performance.
    2. To demonstrate the characteristic change of key indicators and processes in the internal combustion engine affected by the change of engine operating regimes.

Additional objectives:
    1. To demonstrate the sequence of actions to optimize the engine valve timing.
    2. To demonstrate the sequence of actions to optimize ignition 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 10 ... 12)
4. Maximum RPM
5. Cooling system (liquid, air)
6. Engine application area
7. Boosting system (it is usually recommended to use naturally aspirated engine without exhaust gas recirculation).
8. Number of valves per cylinder

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 given. 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**.

Step 2

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.

Step 3

Click ![icon] 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 4

Click ![icon] 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 RPM for the idling mode placed in the last column.

- Set the RPM value at different operating modes with equal incremental change. Set the RPM for each mode as shown in Fig 1.

- Set the air fuel equivalence ratio for each mode. For simplicity, it can be set as $\alpha = 1$ for all modes.

α	Engine type
1.0	Petrol engines with fuel injection and 3-stage catalytic converter
0.95 … 1.05	Carbureted engines
0.75 … 0.85	Aviation engines during intake mode

- Set the ignition timing for each mode as shown in Fig 1.

- Set the ambient temperature (standard temperature for aviation engines: $T_o=288$ К; for others: 293 K or 298 К).

- Set the inlet pressure losses and differential pressure in the exhaust for each mode as shown in Fig 1. The maximum losses in the exhaust occur at full power and usually reach 0.04 bar. Inlet pressure loss is a controlling parameter for required engine power. This parameter for each model will be corrected at the later stages.

- For engines with direct fuel injection, the same injection timing can be set for all the operating modes.

- Units of injection timing: crank angle degrees before TDC, for intake and power strokes.

- Initially the same injection duration can be applied to all modes.

Make sure to give an appropriate name to a specific mode. This will help with identification of a needed mode.

Fig 1. Operating mode table

Note that the preprocessor has internal logic and required windows and input spaces appear only if the relevant data are needed for the calculation of the selected type of the engine.

If you struggle with the selection of empirical coefficients then use the default values of **Wizard of New Project Creation**.

Step 5   First calculation of maximum 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 Fig 1) 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 Fig. 1) 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 6

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 provide in the software tutorials. (<Help> or button)

Check the calculated maximum engine power. If it differs from the one declared by the engine manufacturer more than 3% you should consult with your instructor and correct the following:

- configuration of intake and exhaust valves, see Appendix 1;
- intake and exhaust valve timing (intake and exhaust valve timing should be optimized at maximum torque);
- spark advance angle;
- air equivalence ratio α;
- empirical coefficients for combustion, heat transfer, gas exchange, and mechanical losses.

Step 7 Calculation of Maximum Torque

Set the parameters in Operating Mode ⟨icon⟩ (Fig 1) for "Maximum Torque" mode $RPM_{MaxTorq} \approx (0.48 \dots 0.6)\ RPM_{MaxPower}$ (usually 2500 … 3500 RPM).
Inlet pressure losses: $dp_{int\_MaxTorq} \approx 0.6\ dp_{int\_MaxPower}$
Differential pressure in the exhaust: $dp_{exh\_MaxTorq} \approx 0.25\ dp_{exh\_MaxPower}$

Compute the case at "Maximum Torque".

Step 8   Optimization of the engine intake valve closing at the Maximum Torque (RPM=3500)

Select 1D scanning: <Optimization => Scanning => Radio button 1D scanning>.
Select an argument for scanning: IVC (Intake Valve Closing).
Click [>>] button and in appeared window insert:
   - Min. Value IVC: 5 deg. after BDC,
   - Max. Value IVC: 65 deg. after BDC,
   - Number of calculating points: 7.
Click OK close the window and perform scanning.

Plot the volumetric efficiency (*Eta_v*) vs. IVC. Fix this as an optimum result, i.e. insert IVC value at maximum *Eta_v* as an input parameter for intake valve closing:
<Gas Exchange System => Inlet valve Timing> .
Explain why curve *Eta_v (*IVC*)* has a defined maximum.

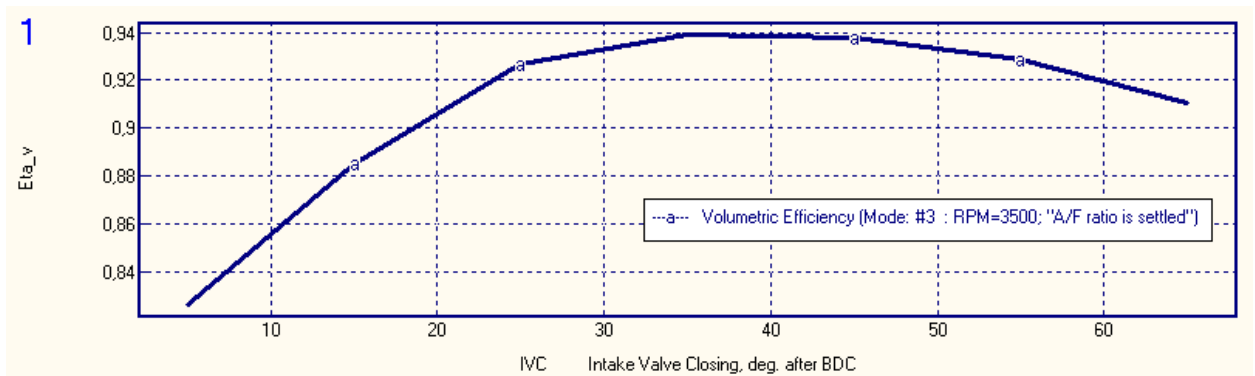
Fig 2. Volumetric efficiency *Eta_v* vs. Intake Valve Closing (IVC)

The optimum value of volumetric efficiency at maximum Torque is *Eta_v* = 40 deg. after BDC.

Step 9   Optimization of the engine intake valve opening at the Maximum Torque (RPM=3500)

Select 1D scanning: <Optimization => Scanning => Radio button 1D scanning>.
Select an argument for scanning: EVO (Exhaust Valve Opening).
Click [>>] button and in appeared window insert:
   - Min. Value EVO: 15 deg. after BDC,
   - Max. Value EVO: 75 deg. after BDC,
   - Number of calculating points: 7.
Click OK close the window and perform scanning.

Plot Indicated Mean Effective Pressure (IMEP), Pumping Mean Effective Pressure (PMEP) and Break Mean Effective Pressure (BMEP) vs. EVO.

Fix this as an optimum result, i.e. insert EVO value at maximum BMEP as an input parameter for exhaust valve opening:
<Gas Exchange System => Exhaust Valve Opening>
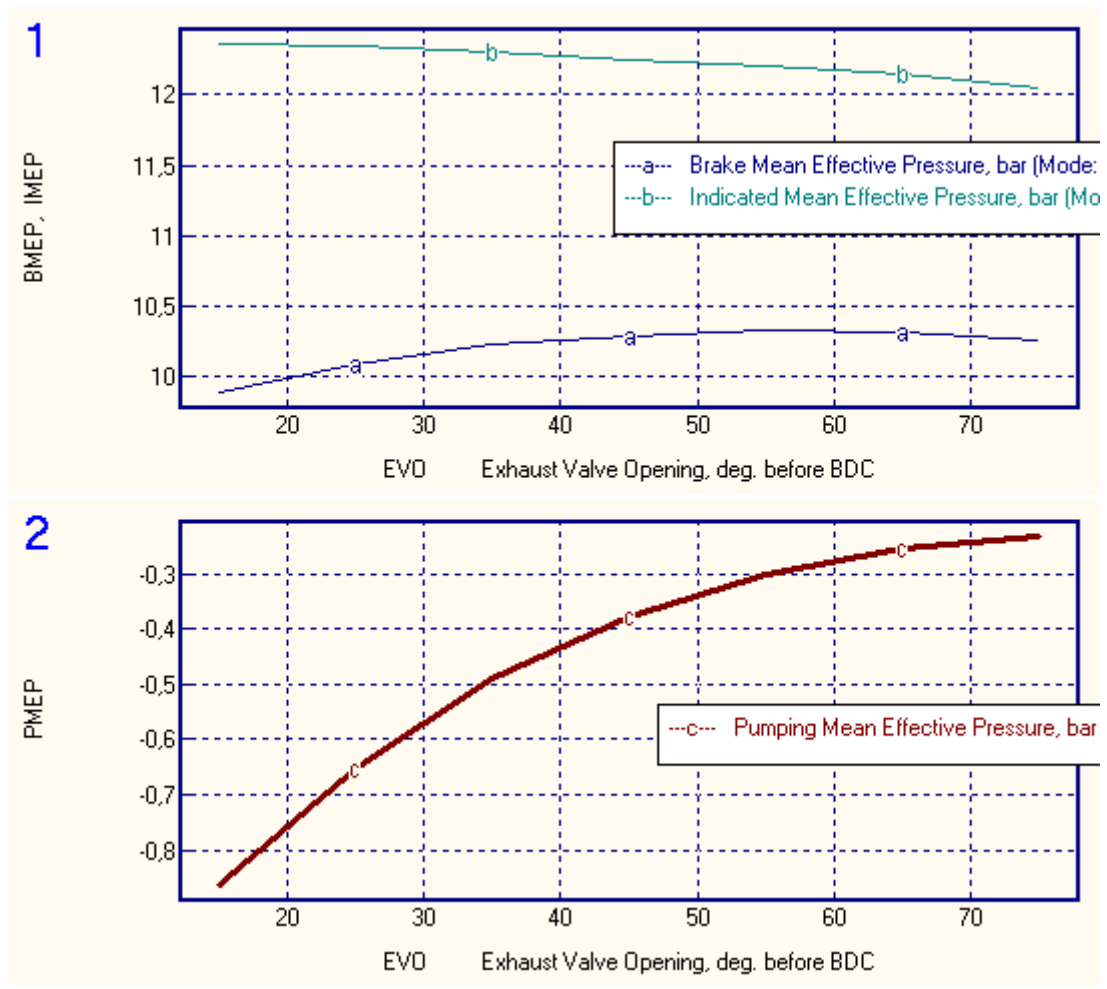Explain why curve BMEP (EVO) has a defined maximum.

Fig 3. Break Mean Effective Pressure (BMEP), Indicated Mean Effective Pressure (IMEP) and Pumping Mean Effective Pressure (PMEP) vs. Exhaust Valve Opening (EVO).

The optimum exhaust valve opening at maximum Torque is EVO = 57 deg. before BDC.

Step 10   Optimization of the spark advance angle at the Maximum Power

Select 1D scanning: <Optimization => Scanning => Radio button 1D scanning>.
Select an argument for scanning: *Theta_i* (Ignition Timing).
Click [>>] button and in appeared window insert:
   - Min. Value *Theta_i*: 15 deg. before TDC,
   - Max. Value *Theta_*i: 35 deg. before TDC,
   - Number of calculating points: 7.
Click OK close the window and perform scanning.

Plot Indicated Specific Fuel Consumption (SFC) vs *Theta_i*.

Fix this as an optimum result, i.e. insert *Theta_i* value at the minimum SFC as an input parameter for *Theta_i* in table of Fig 1:
<Gas Exchange System => Exhaust Valve Opening>
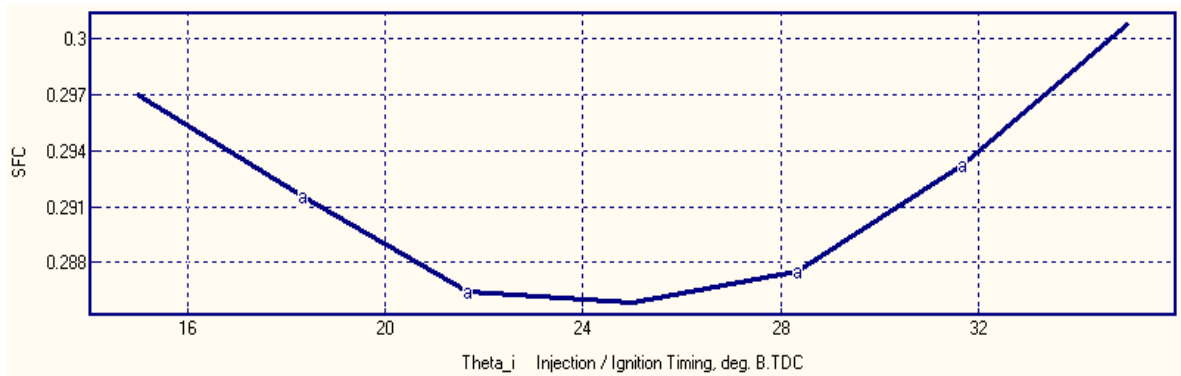Explain why curve DFC (*Theta_i*) has a defined maximum.

Fig 4. Specific Fuel Consumption (SFC) vs. Spark Advance Angle (*Theta_i*).

The optimum spark advance angle at Maximum Power is *Theta_i* = 25 deg. before TDC.

Step 11

Assign a spark advance angle in Fig 1 for all engine operation regimes (RPM) in accordance with the correlation shown in Fig. 5
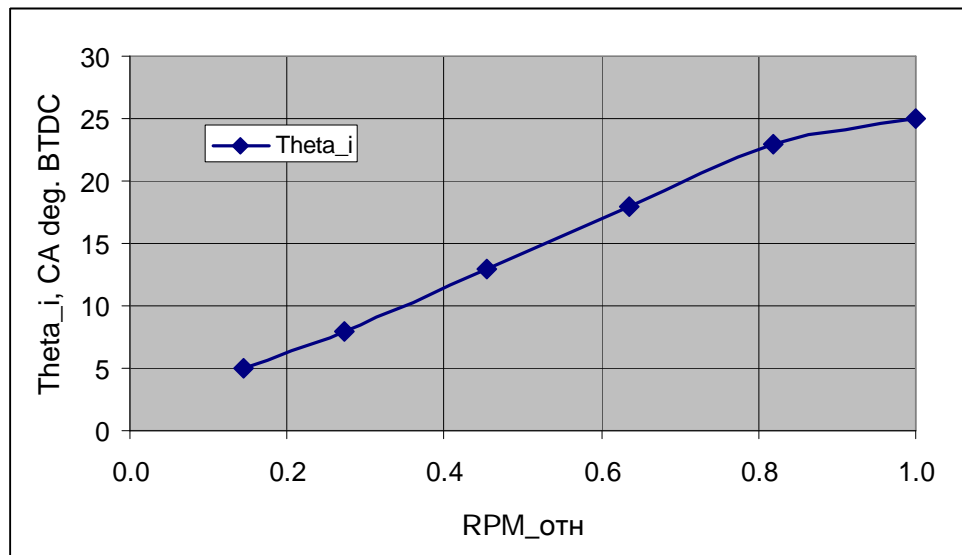
Fig 5. Correlation of spark advance angle (Theta_i) vs. RPM/RPM$_{max}$

Step 12

Select the Inlet Pressure Loss value at engine idling such that the computed power does not exceed 5kW. For this, compute only for the required mode. You can do the mode selection either by selecting in the table of Fig 1 or by using *Run* window as shown in Fig 6.
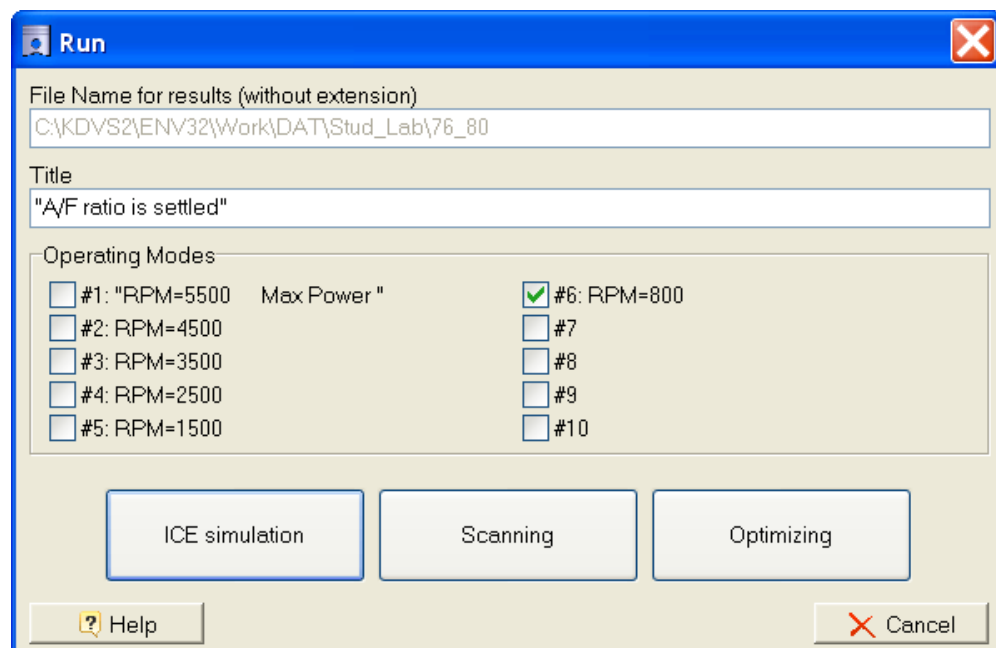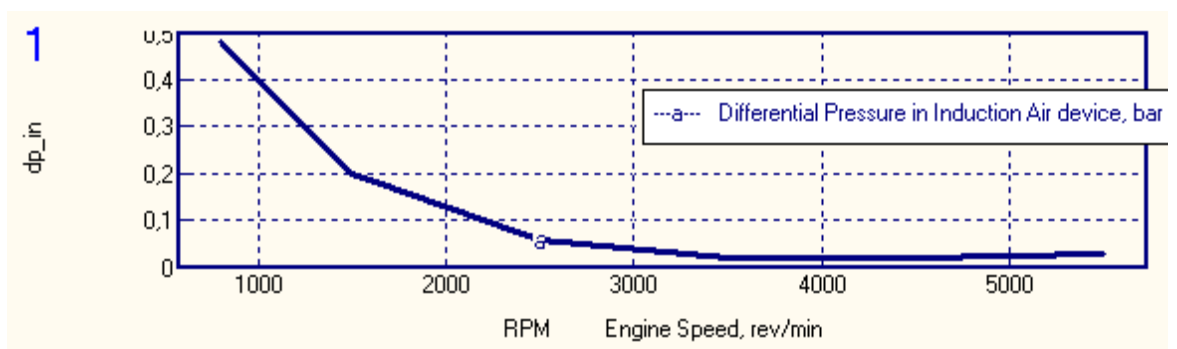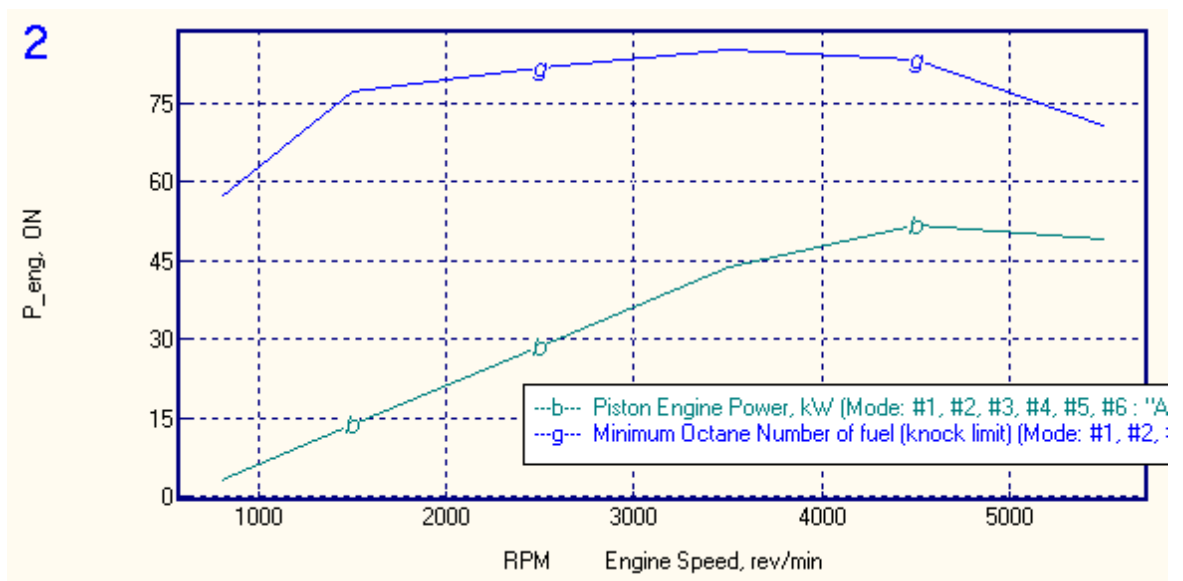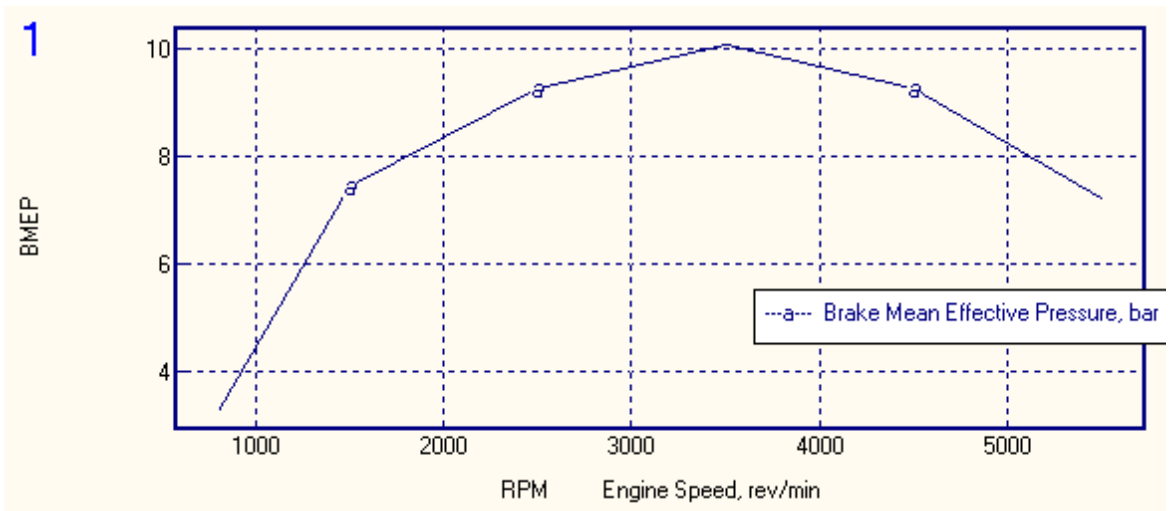

Fig 6. "*Run*" window.

Select the Inlet Pressure Loss values for other remaining regimes to achieve a smooth increase of power and torque as shown in Fig 7a and 7b, avoiding knocking condition. Calculated Octane Number should not exceed (Fuel Octane Number - 10) as shown in Fig 8.

Fig 7a. Break Mean Effective Pressure vs. RPM

Fig 7b. Engine Power and Minimum Octane Number of Fuel vs RPM

Fig 8. Induction Differential Pressure vs. RPM

Plot the Break Torque, the Maximum Cylinder Pressure and the Specific Fuel Consumption vs. RPM as shown in Fig 9
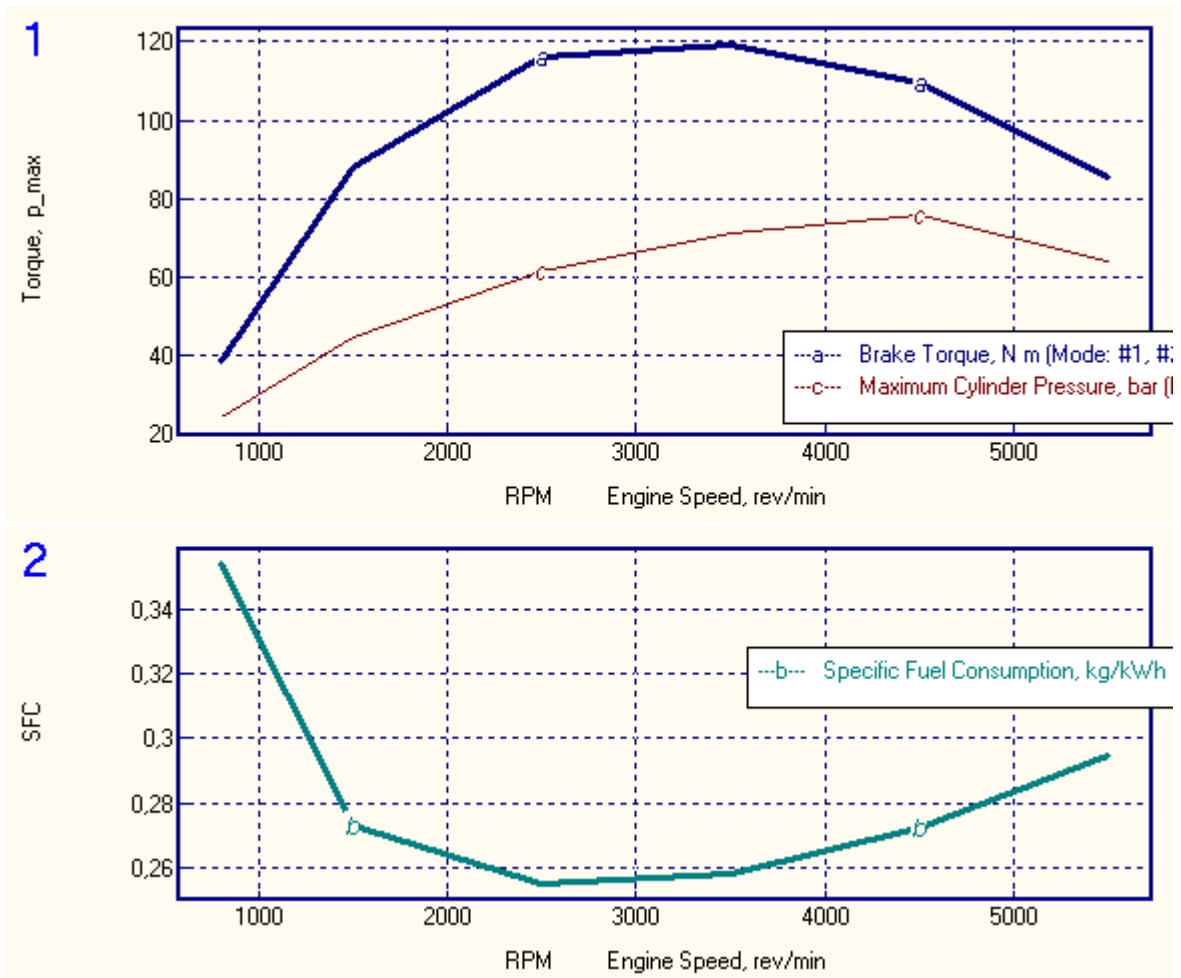
Fig 9. Brake Torque, Maximum Cylinder Pressure, and Specific Fuel Consumption vs.
RPM

Step 13

Analyze the engine operation at maximum power (RPM=5500) and low power
(RPM=1500) with optimized valve opening and closing and compare in-cylinder
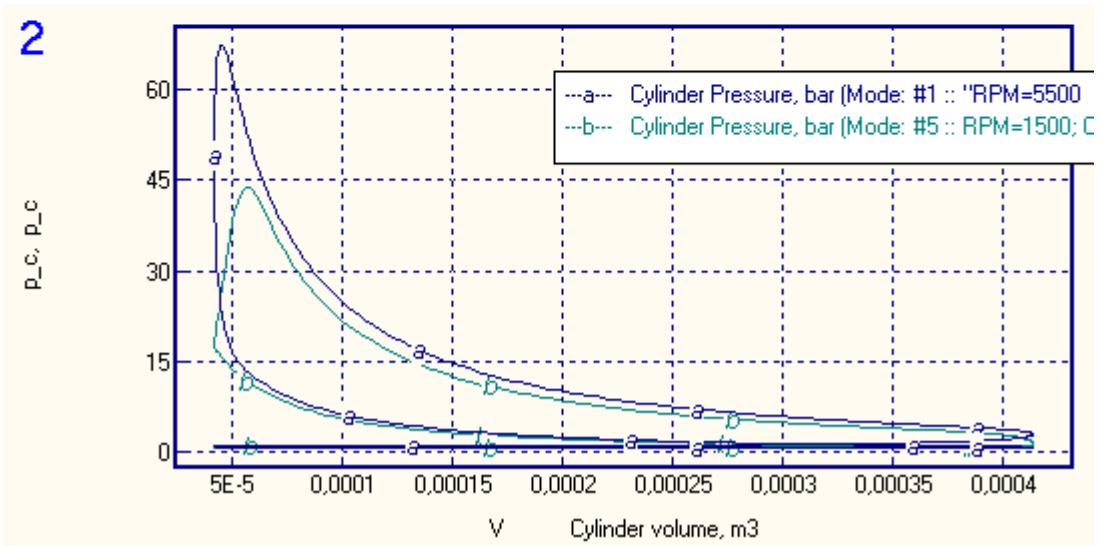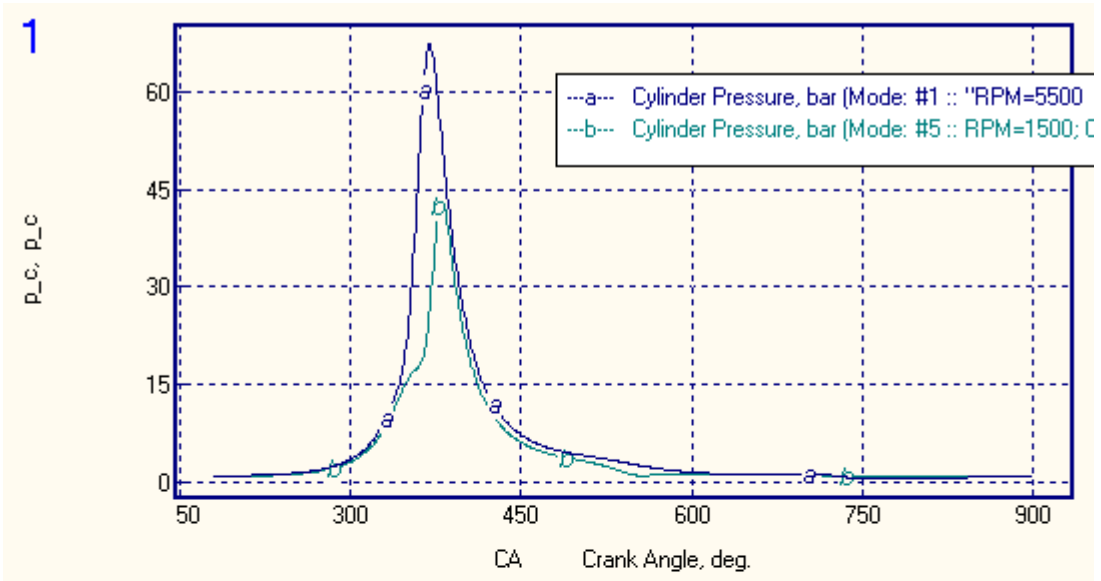pressure trends (bar) vs. RPM and vs. Cylinder Volume (m^3), as shown in Fig 10.

Fig 10. Cylinder Pressure vs Crank Angle Degree and vs. Cylinder Volume

Appendix 1

Modification of gas exchange system

It should be noted that for modern high-speed or racing gasoline engines the initial computation using the default values, which are available via New Project wizard, may produce power levels much lower than those specified by the engine manufacturer. This is because the default values in the project wizard were not assigned for gas exchange systems of the forced racing engines types, but mainly for naturally aspirated engines with moderate speed. An indication of incorrect input data for intake and exhaust system can be the engine volumetric efficiency $h_v < 0.92$. Therefore, in order to correctly assign the gas exchange parameters more technical information is required about the size of intake and exhaust valves of a given engine or the engine of similar type. For example: for BMW S62B50 engine the data provided in the table below can be used.

Technical Data	MS S62
Valve diameter Intake / Exhaust (mm)	35 / 30.5
Stem diameter Intake / Exhaust (mm)	6 / 6

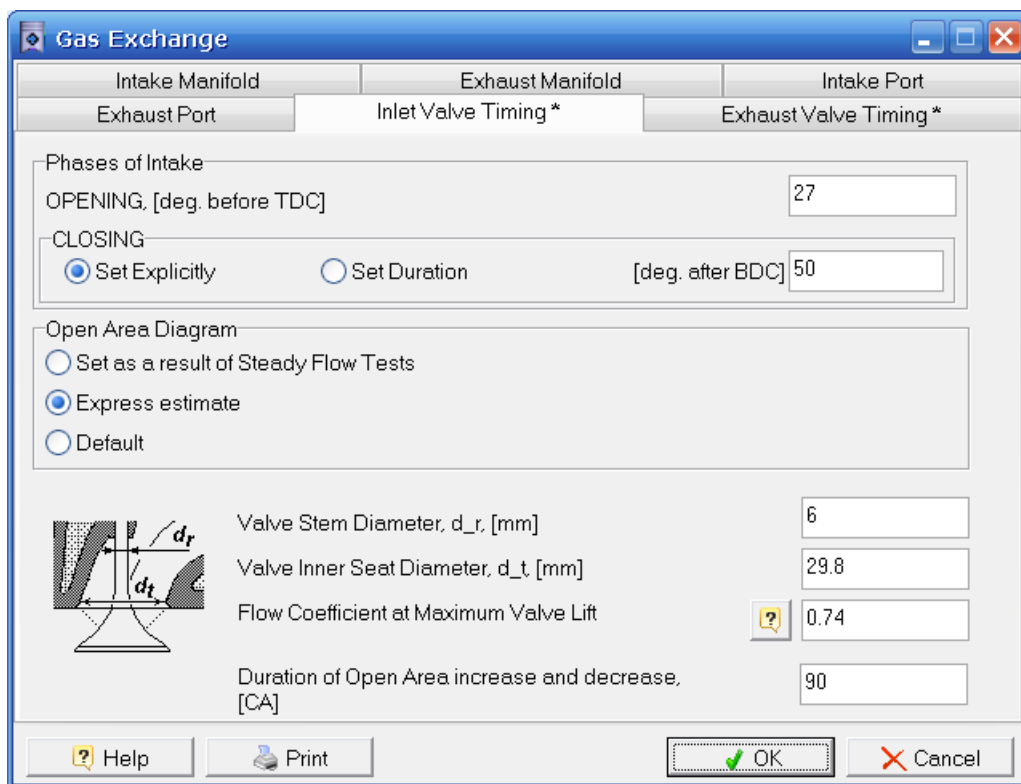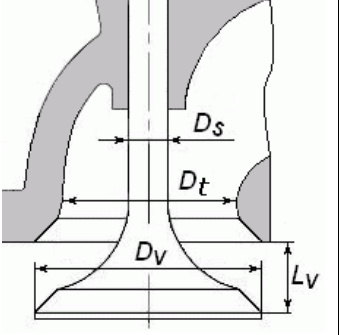Click button that opens gas exchange parameter control window:

Fig 11. Gas Exchange parameter control window

Under "Open Are Diagram" option select "Express estimate". Insert the value for Valve Stem Diameter, D_s, Valve Inner Seat Diameter, D_t and Flow Coefficient at Maximum

Valve Lift m in accordance with recommendations given in [1]. Also set "Duration of Open Area Increase and Decrease" $F_{inc\,/dec}$. If these data are not available for forced engines you can use values given in the table below:

Intake	Exhaust	
$D_s = (0.2…0.22)\,D_v$ [mm]	$D_s = (0.23…0.25)\,D_v$ [mm]	
$D_t = 0.85\,D_v$ [mm]	$D_t = 0.89\,D_v$ [mm]	
$m = 0.74$	$m = 0.78$	
$F_{inc\,/dec} = 90^0$ [CA]	$F_{inc\,/dec} = 90^0$ [CA]	
$L_v = 0.25\,D_v$ [mm]	$L_v = 0.25\,D_v$ [mm]	

For the forced and high-speed engines the valve overlap for intake and exhaust can be larger than for naturally aspirated engines. To determine the right angles for exhaust valve opening and intake valve closing you have to perform 2D parametric study to find out the effect of these factors on engine performance. To perform 2D scanning use the main menu "Optimization => Scanning" and select "2D Scanning" option.
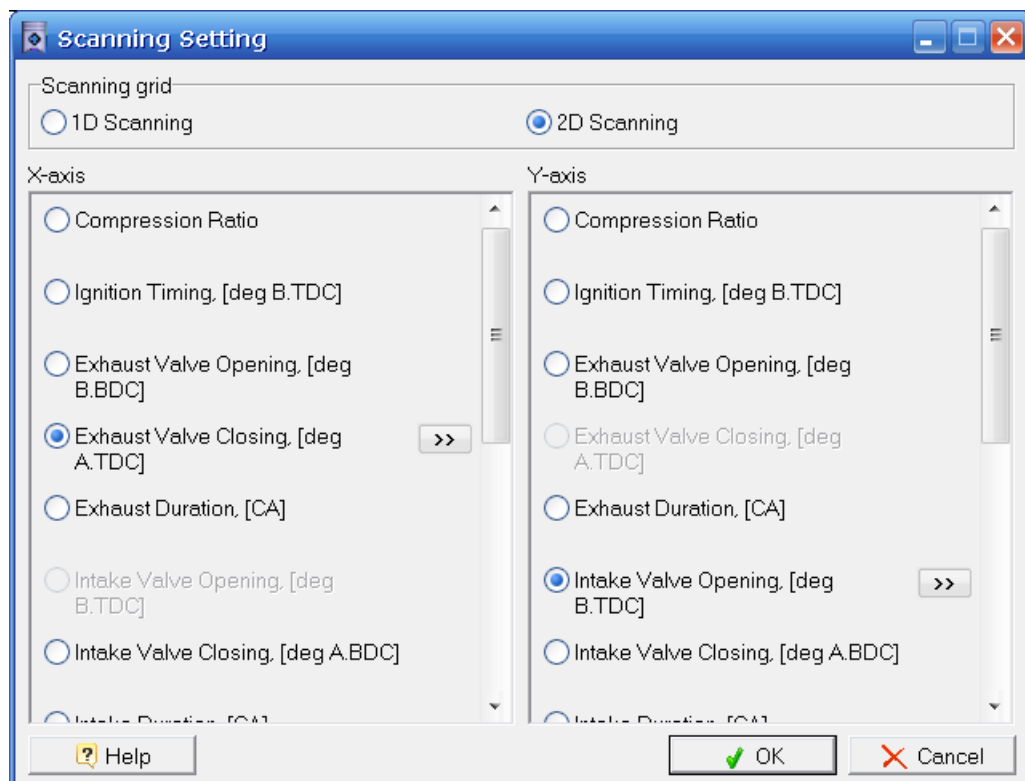

Fig 12. Scanning Setting window

Click [>>] button and set the range for parameters assigned for X and Y, as well as the number of calculating points, as shown in Fig 13.

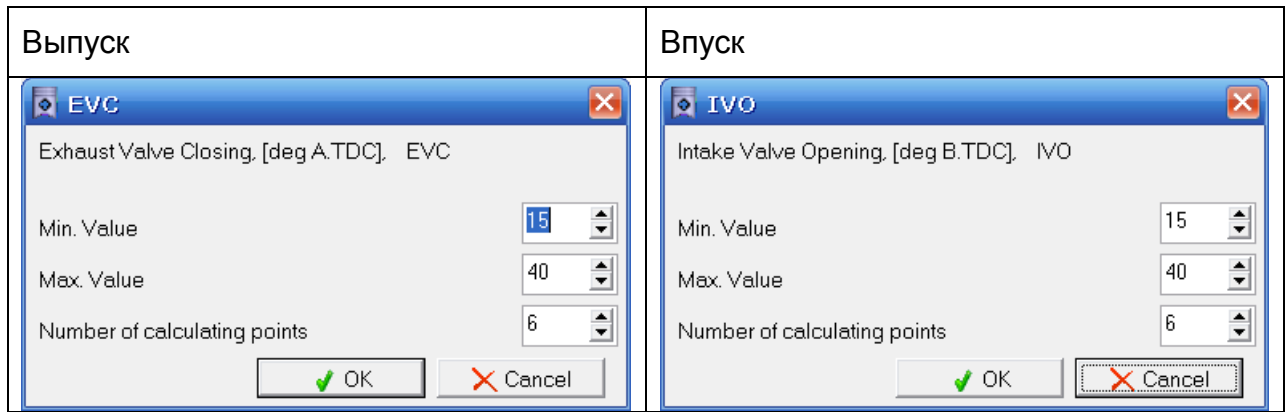| Выпуск	Впуск

Fig 13. Exhaust Valve Closing (EVC) and Intake Valve Opening (IVO) value setting for 2D scanning

Perform 2D scanning by clicking button. In the appeared window click **"Scanning".**

Results can be viewed by selcting "Isolines" window that can be opened via main menu "Results => 2D Results":
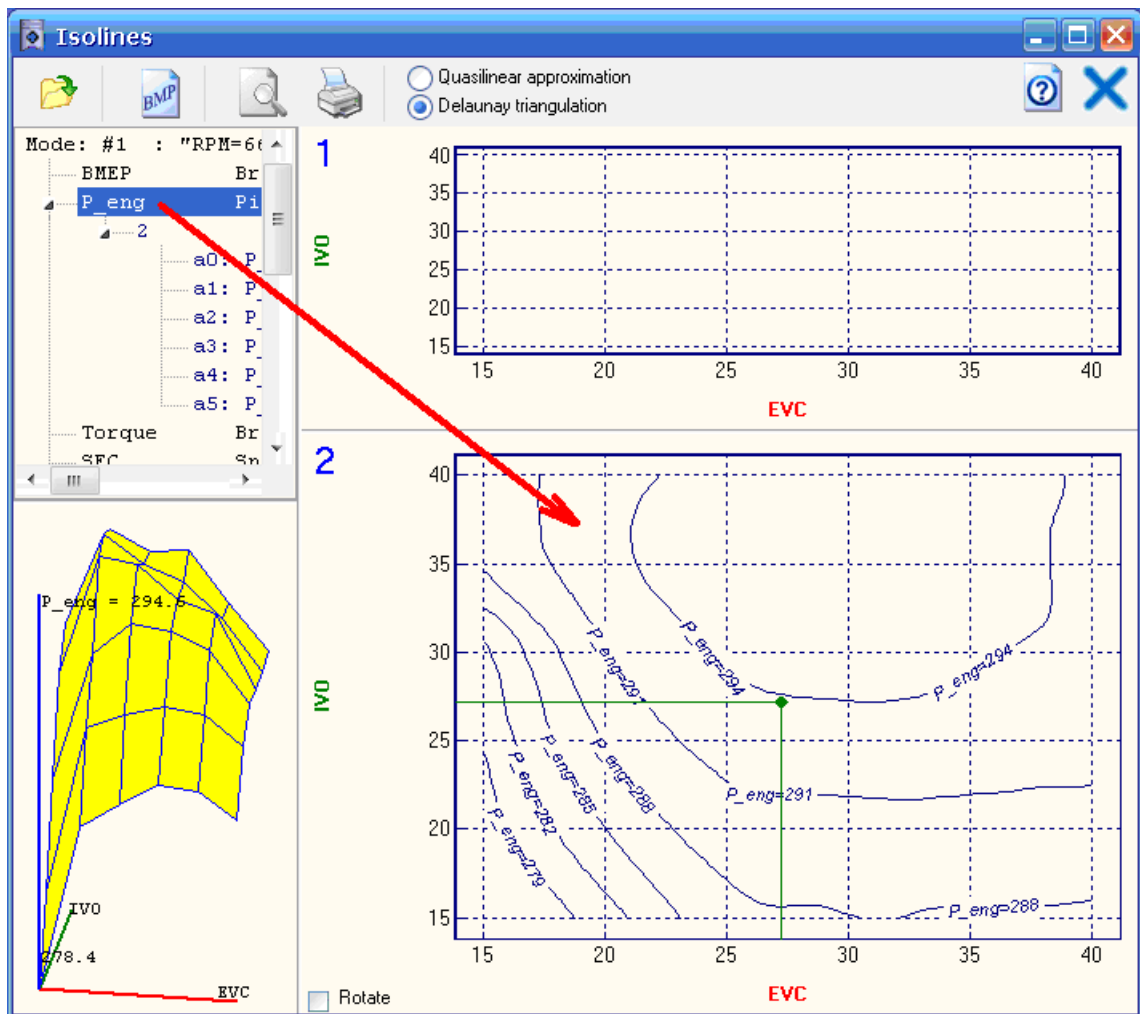

Fig 14. 2D scanning output window

To plot the collection of isolines, drag the designated parameter by the mouse to the panel as shown in Fig 14.

3D surface of the function may be considered in a more detailed interpretation and from different angles by double-clicking on it. You can click the right button of the mouse and rotate the image.
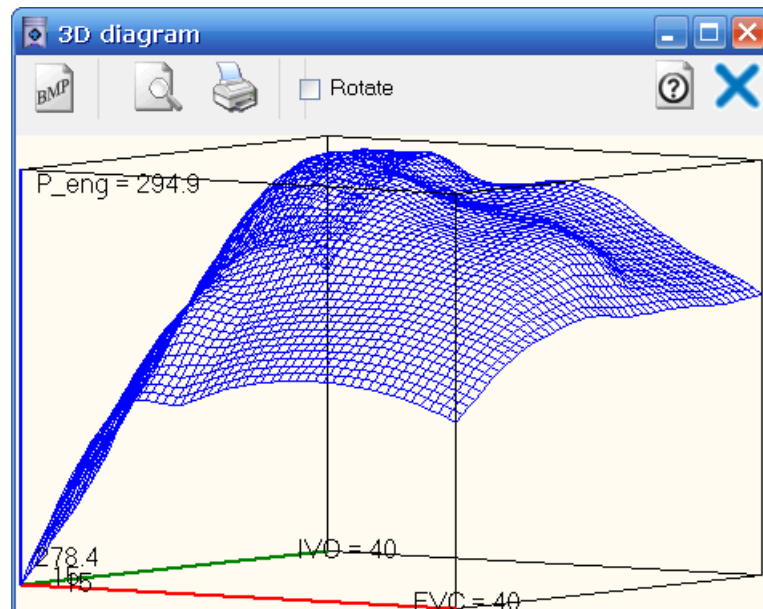

Fig 15. 3D diagram of 2D scanning

Methods of editing the isoline contours are presented in Help.

When selecting the valve overlap it should be noted that the large overlap will lead to a significant deterioration of the engine parameters and performance at partial loads, during throttling. Therefore, the valve overlap value should be selected carefully. For example, we can select:
  • The angle for exhaust closing 27 deg. after TDC;
  • The angle for intake valve opening 27 deg. before TDC.

The selected angles for intake and exhaust (indicated by a green dot on Fig. 14) should be inserted into the window in Fig. 11.

Set the air fuel equivalence ratio at Maximum Power mode close to stoichiometric, $\alpha \sim 0.95$, in Operating Mode table (Fig 1.) and perform calculation as described in Step 5.

If it wasn't possible to achieve the desired increase in engine power you should try to control the other processes.

References

1. Andrey Kuleshov, Leonid Grekhov Multidimensional Optimization of DI Diesel Engine Process Using Multi-Zone Fuel Spray Combustion Model and Detailed Chemistry NOx Formation Model // SAE Paper No 2013-01-0882. – 2013, 20 p.

2. Andrey Kuleshov, Khamid Mahkamov, Andrey Kozlov, Yury Fadeev Simulation of dual-fuel diesel combustion with multi-zone fuel spray combustion model // ASME 2014 Internal Combustion Engine Division Fall Technical Conference ICEF2014-5700, October 19-22, 2014, Columbus, IN, USA, 14 p.

3. Leonid Grekhov, Khamid Mahkamov, Andrey Kuleshov Optimization of Mixture Formation and Combustion in Two-stroke OP Engine Using Innovative Diesel Spray Combustion Model and Fuel System Simulation Software // JSAE Paper No: 20159328 SAE Paper No 2015-01-1859. – 2015, 17 p.

4. Kuleshov A.S. Model for predicting air-fuel mixing, combustion and emissions in DI diesel engines over whole operating range // SAE Tech. Pap. Ser. – 2005. – N 2005-01-2119. – P. 1-16.

5. Kuleshov A.S. Use of Multi-Zone DI Diesel Spray Combustion Model for Simulation and Optimization of Performance and Emissions of Engines with Multiple Injection // SAE Tech. Pap. Ser. – 2006. – N 2006-01-1385. – P. 1-17.

6. **[1] Kuleshov A.S. Multi-Zone DI Diesel Spray Combustion Model and its application for Matching the Injector Design with Piston Bowl Shape // SAE Tech. Pap. Ser. – 2007. – N 2007-01-1908. – P. 1-17. doi:10.4271/2007-01-1908.**

7. Kuleshov A.S. Multi-Zone DI Diesel Spray Combustion Model for Thermodynamic Simulation of Engine with PCCI and High EGR Level // SAE Tech. Pap. Ser. – 2009. – N 2009-01-1956. – P. 1-21.

8. Kuleshov A., Mahkamov K. Multi-zone diesel fuel spray combustion model for the simulation of a diesel engine running on biofuel // Proc. Mechanical Engineers. – 2008. –Vol. 222, Part A, Journal of Power and Energy. – P. 309-321.

9. **[1] Kuleshov, A., Kozlov, A., and Mahkamov, K., "Self-Ignition Delay Prediction in PCCI Direct Injection Diesel Engines Using Multi-Zone Spray Combustion Model and Detailed Chemistry," SAE Technical Paper 2010-01-1960, 2010, doi:10.4271/2010-01-1960.**

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[1] **Use these papers for citation in the first place.**