FEDERAL AGENCY OF EDUCATION
State education institution of high professional education
“Moscow state technical university after N.E. Bauman”
(MSTU by N.E. Bauman)

Power Engineering Faculty
Piston Engine Department

Kuleshov Alexey

Diploma Project

Light duty diesel having 60 kW power at 3600 RPM

Supervisor :
Dr. of Sci., prof., Grekhov L.V.

Moscow, Russia
2010

Abstract

In the diploma project there was carried out a computer investigation of a new concept of diesel engine: z-engine. The z-engine concept was patented by Aumet OY (Finland). The designed and investigated diesel engine is intended for passenger car of small class. Corresponding with assignment the engine shoud have 70 kW power at 3600 RPM, S/D = 70/72 mm, at the maximum torque operating mode engine should have BMEP = 26 bar. However, after thermo-dynamic analysis the was discovered the engine can have only 60 kW power at 3600 RPM, otherwise if 70 kW required the fuel consumption and soot emission will be too large. The adopted value of maximum cylinder pressure is 200 bar, the fuel injection system is Common Rail. The main advantages of z-engine in comparison with conventional DI diesel engines are:

- very law level of NOx emission achieved without external EGR system and catalyst;
- small size because one has in 2 cylinders same power as 4 cylinder 4 stroke DI diesel engine;.
- low production cost because one has smaller number of cylinders and has not external EGR system;
- good part load efficiency being better than 4 cylinder 4 stroke DI diesel engine has;
- excellent transient behavior is provided by 2 stroke cycle and supercharger.

The diploma project includes development the engine drawings (longitudinal and cross sections), thermodynamic analysis of the z-engine in comparison with 4 cylinder 4 stroke DI diesel engine, analysis, design and optimization of the z-engine piston because one works in very hard conditions and calculations of main elements.

The project was ordered and supported by Aumet OY being the developer of the z-engine concept.

Content

Introduction

Now days the most actual problems staying before transport engine manufacturers are the exhaust gas emission control and fuel efficiency improvement. The abilities of conventional engines refinement are already mainly expended. To improvement the engines ecologic the following main solutions are used.

1. The catalyst.

Advantages: - Easy design and mounting.

- Small effect in power and fuel consumption.

Disadvantages: - High cost.

- There is a defilement of the working surface of catalyst by unburned fuel and lubricating oil.
- There is a small resource at frequent engine stop and start.

2. Water injection.

Advantage: - NOx may be reduce in 40 %.

Disadvantages: - Water should be protected against freezing.

- Water initiates the corrosion of metals.

- There is a necessity of additional engine system for water tankage and supply.

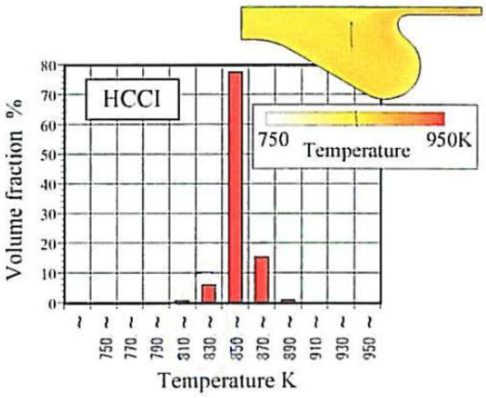
3. **Alternate fuels:** DME, Ethanol, Natural gas, Pipeline gas, Hydrogen, Syngas, Biogas, etc.

Disadvantage: A special infrastructure is necessary for transport engines supply.

4. SRC – Selective Catalytic Reduction

Disadvantages:
- SRC should be protected against freezing.
- SRC initiates the corrosion of metals.
- There is a necessity of additional engine system for SRC tankage and supply.
- A special infrastructure is necessary for transport engines supply.

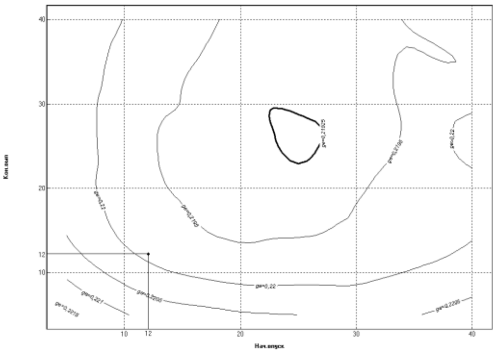
5. HCCI – Homogenous Charge Compression Ignition

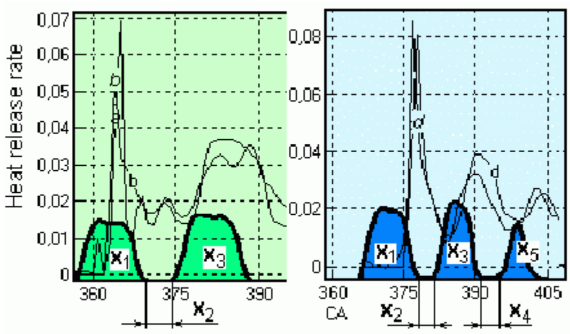


Disadvantages:
- HCCI can not be arranged at large power operating modes.
- There are problems with the combustion control.

6. Optimization of conventional engine cycle:

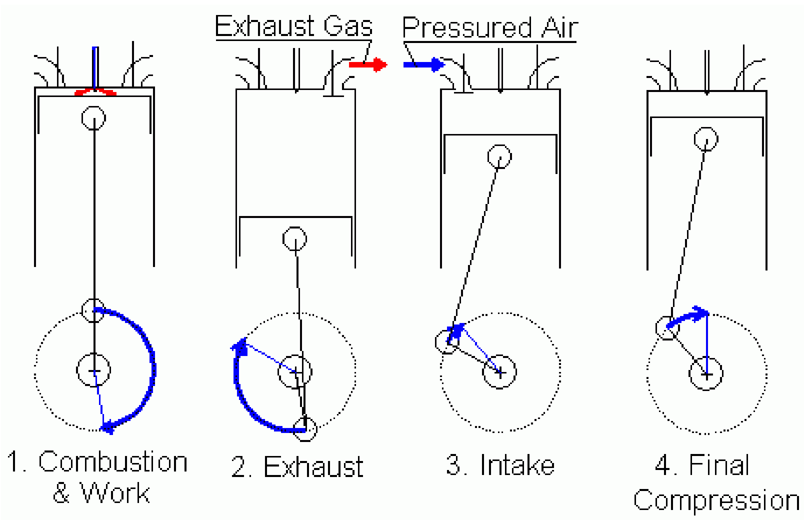
EGR and multiple injection strategy optimization.





Disadvantage: The resources are mainly expired and future decrease of NOx emission is concerned with fuel efficiency losses.

7. Z-ENGINE concept of diesel working process.



Advantages: - NOx emission is less 1 g/kW h in whole engine operating map.

- Downsize the DI diesel engine.
- Low production cost (no catalytic converter and two times smaller number of cylinders).
- High BMEP.
- Good part load efficiency.
- Good transient behavior.

This cycle is patented by Aumet Oy Company.

Disadvantages: - Complicated valve train mechanism.

- Large fuel consumption at high load.

The aim of this project is a general development of the z-engine DI diesel concept for passenger car application. It includes:

- Engine working cycle analysis with thermodynamic engine simulation tool DIESEL-RK (www.diesel-rk.bmstu.ru). Comparison of the calculated data with corresponding 4-cylinder 4-stroke DI diesel engine.
- Finite Element Analysis of the z-engine piston, connecting rod and piston pin, at maximum torque operating point.
- Development of the z-engine drawings.
- Dynamic analysis of the crank-piston mechanism.
- Analysis of the strength state of main engine parts.

Downsizing of the high speed DI diesel engine is illustrated by Fig. 1. where the 2 cylinder 2 stroke z-engine has the same power as 4 cycle 4 cylinder diesel engine.

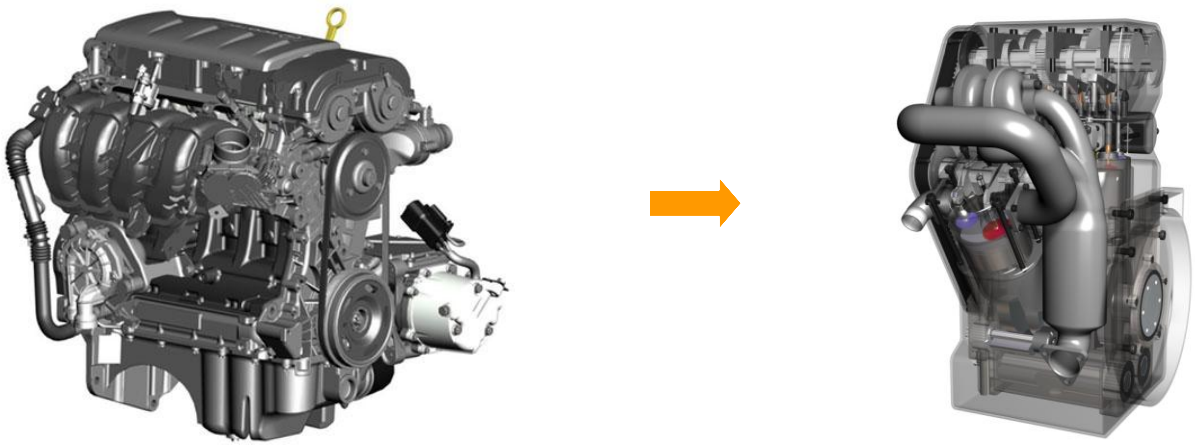


Figure 1. Downsizing of the high speed DI diesel engine

The scheme of boost including one stage turbocharger and intercooled EGR system is replaced with two-stage boost with piston supercharger and second intercooler of pressured air, Fig.2.

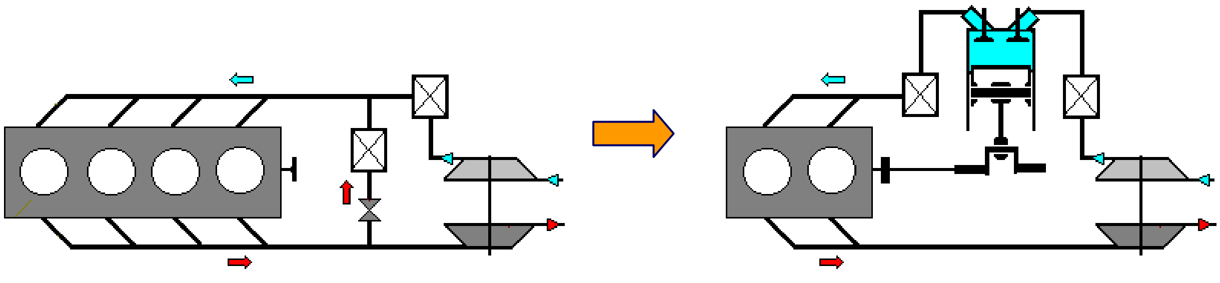


Figure 2. Boost of z-engine in comparison with conventional DI diesel engine.

Working cycle of z-engine starts from conventional fuel injection, combustion and expansion (work stroke), Fig. 3.

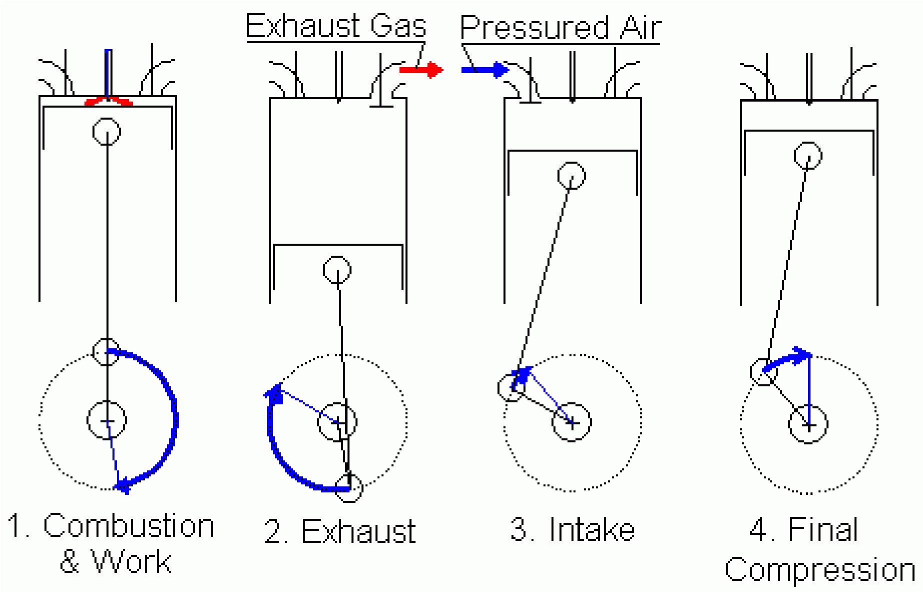


Figure 3. The z-engine working cycle.

Exhaust starts as in conventional HSDI diesel engine: EVO = 65-70 deg. BBDC and continues up to 110-115 deg. ABDC. Valve open diagram is presented in the Fig. 4. Z-engine has 2 conventional exhaust valves and 2 intake valves. Because intake air pressure is very high (about 16-17 bar) and intake air is cold (intake temperature is about 320 K) the density of fresh charge is about 19.6 kg/m^3. It allows make intake very short (16 deg.), and maximum effective flow area of the intake can be same as one being in the conventional engine. During the exhaust the in-cylinder pressure continues to be small until the intake period starts. During the intake the in-cylinder pressure increases rapidly, Fig. 4. Intensive intake flow taking place near the TDC increases air turbulence and make future mixture formation and combustion more intensive. After the short intake the fresh charge is compressed finally and fuel injection takes place as in conventional diesel engine.

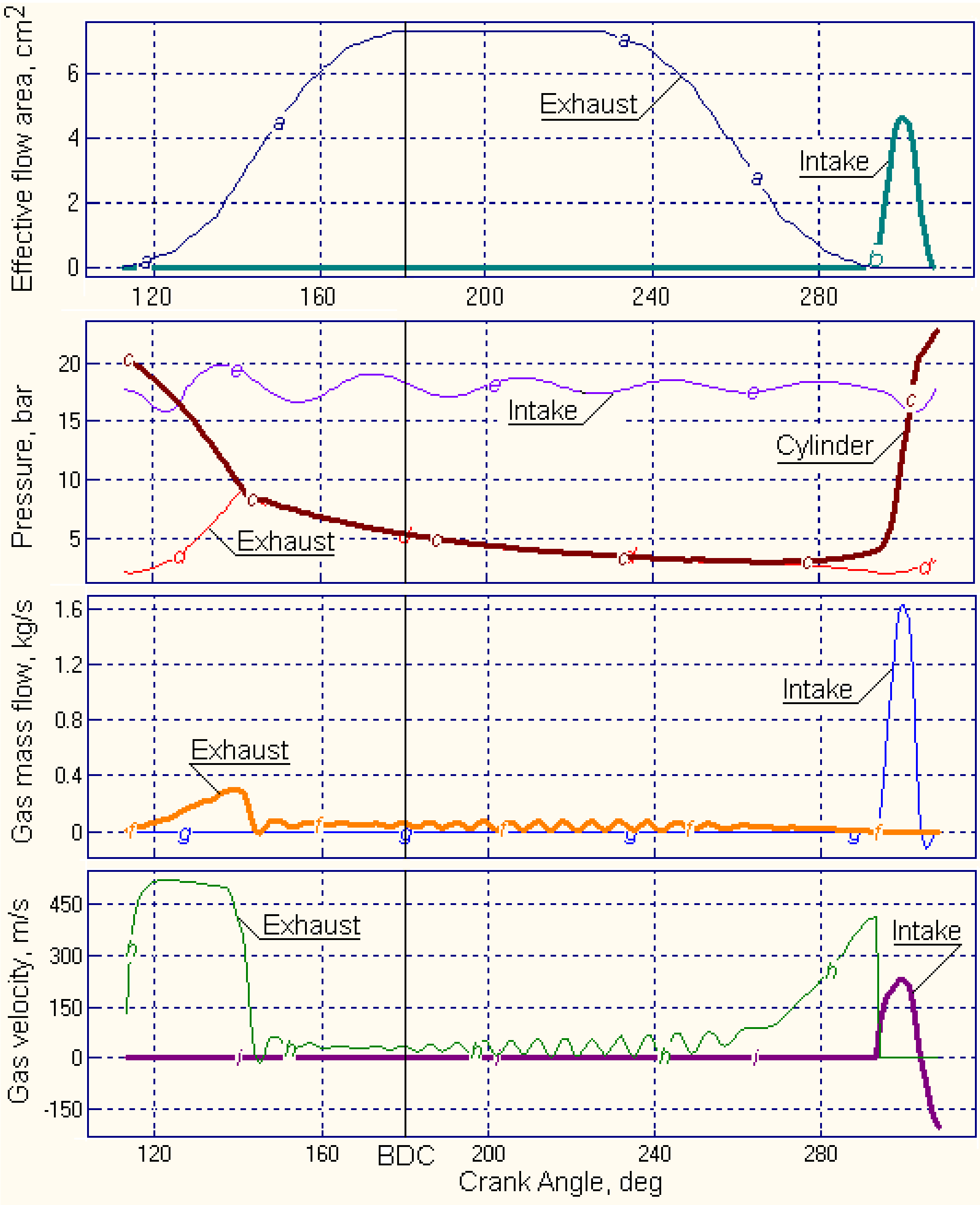


Figure 4. Gas exchange in the z-engine.

The *p*-*V* and *T*-θ diagrams of the z-engine are shown in the Fig. 5. in comparison with the same diagrams of a conventional 4 cylinder 4 stroke DI diesel engine at the same operating point: BMEP=26 bar@1500 RPM. Both engines have S/D = 70/72 mm and CR=15.5; Cycle fuel mass = 0.053 g/cycle; Air mass (Air/Fuel eq. ratio=1.52; Double injection (0.15 pilot + 0.85 main); Injection pressure = 1400 bar; Turbocharger pressure ratio PR=4.3.

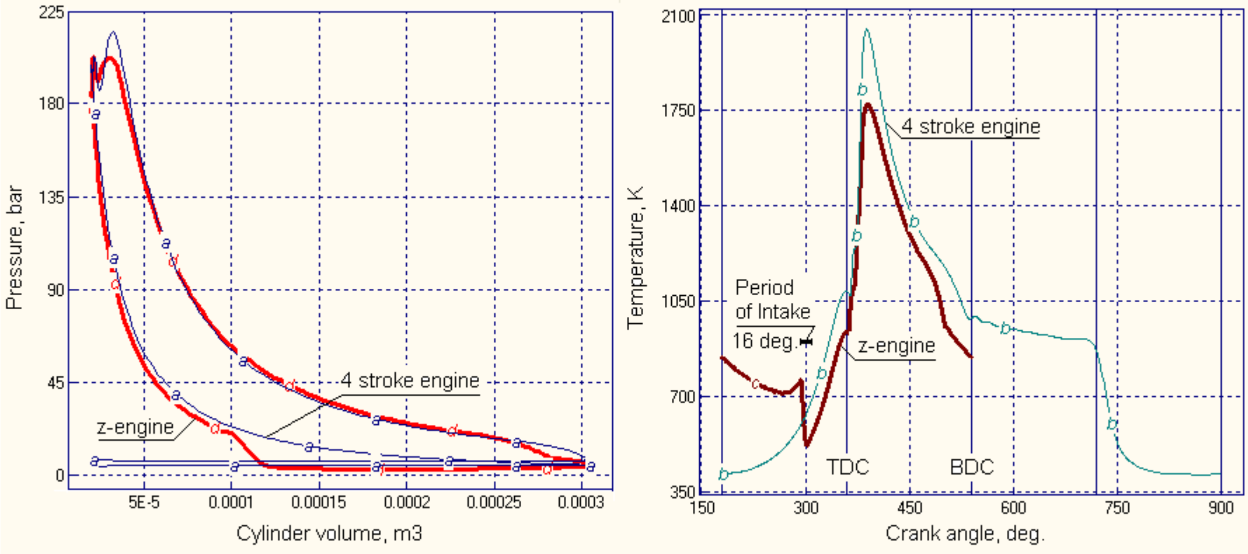


Figure 5. The p-V and T-θ diagrams of the z-engine in comparison with the same diagrams of a conventional 4 cylinder 4 stroke DI diesel engine

The p-V diagram of the z-engine (plotted by red) shows the advantage of this concept in the compression work in comparison with the 4 stroke diesel (plotted by blue). This additional work will be spent to drive the supercharger.

The T-θ diagram of the z-engine illustrates the rapid decrease of the in-cylinder temperature during intake stroke due to very small temperature of the very dense fresh charge. It allows not only economy of the compression work before TDC, but realize combustion at relatively low temperature. Last opens the wide perspectives to achieve low NOx emission. The presented trends were confirmed by experimental data being obtained on the test rig in the VTT laboratory (Helsinki, Finland) by Aumet OY.

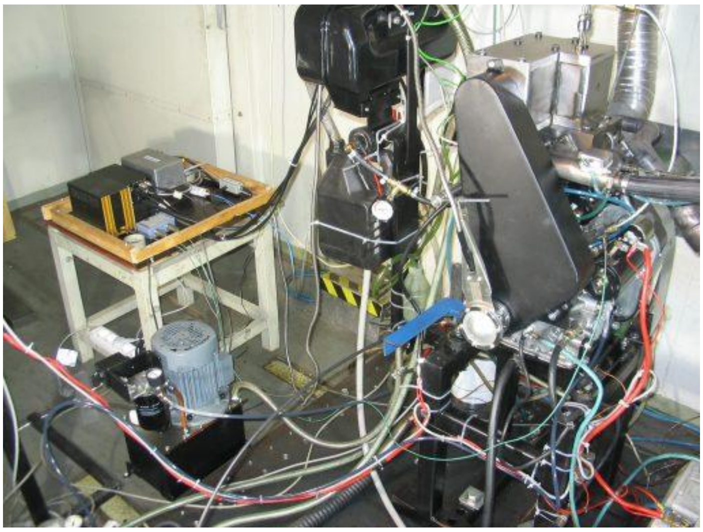


Figure 6. Z-engine on the test rig in the VTT laboratory (Helsinki, Finland)

1. Thermodynamic analysis of the z-engine concept.

Having experimental data including pressure curves, NOx emission, power, etc, the computational research was carried out to find the ways to improve the engine parameters and compare the z-engine concept with conventional diesel engine.

The thermodynamic engine simulation software: DIESEL-RK (www.diesel-rk.bmstu.ru) was used for engine simulation. Because z-engine has unusual temperature behavior at the end of compression the built-in Detail Chemistry model of ignition delay prediction was used.

Because z-engine has relatively high EGR the built-in Detail Chemistry model was used for NOx prediction. Zeldovich model shows too small NOx emission in that conditions.

Z-engine process was optimized (Valve timing, CR, PR of turbocharger and supercharger, injector design, injection timing and strategy of multiple injection were optimized to provide high fuel efficiency and low soot emission) and these optimal solutions were compared with conventional DI diesel engine to discover z-engine advantages and disadvantages.

All empirical coefficients being used for program calibration as well auxiliary units parameters and efficiencies were strictly same for both engines to make this comparison as impartial as it possible.

The main engines data are presented in the Table 1. The main dimensions of the intake and exhaust systems of z-engine were taken from experimental engine developed by Aumet OY (Fig. 6), the main dimensions of 4 stroke engine were taken as typical from light duty engine concept being used nowadays. Parameters of 4 stroke diesel were optimized to reach both minimum NOx and Soot emission as well as minimum Specific Fuel Consumption (SFC). Parameters of z-engine were optimized to achieve minimum SFC, because NOx emission of the z-engine is very small at every cases.

Table 1.

The main data of the 4 stroke DI diesel engine and the z-engine.

Parameter	4 stroke DI diesel	z-engine
S/D, mm	70/72	70/72
Number of cylinders	4	2
Cylinder position	In line	In line
Cooling system type	Liquid	Liquid
CR	16.5	15.5
Max power, kW / RPM	76 / 3600	76 / 3600
Injector	7 x 0.131	8 x 0.131
Fuel injection system	CR	CR
Max. injection pressure, bar	1400	1400
Max. in-cylinder pressure, bar	185	196
Gas exchange system	popped valves	popped valves
Intake: Opening [before TDC] / Duration, deg. Max. eff. Flow area, cm^2	11 / 234 3.83	58 / 16 4.6
Exhaust: Opening [before BDC] / Duration, deg Max. eff. Flow area, cm^2	58 / 253 3.75	68 / 180 7.31
Max. PR /efficiency of turbocharger	4.3 / 0.47	4.3 / 0.47
Max. PR / efficiency of supercharger	-	4.25 / 0.85
Max. external EGR	0.1	-

Z-engine and 4 stroke engine working parameters were simulated at the cases, presented in the table 2.

Table 2.

Calculated operating points of the 4 stroke DI diesel engine and the z-engine.

Case	# 1	#2	#3	#4	#5
RPM	1000	1500	1500	1500	3600
BMEP	3.3	26.1	13.2	6.3	17.4
Cycle fuel mass, g	0.0075	0.053	0.026	0.013	0.034
Injection pressure, bar	648	1394	1448	1100	1488
Injection profile	Single	Double 0.15+0.85	Single	Single	Single
Turbocharger PR	1.01	4.3	2.6	1.4	4.3
Turbocharger Efficiency	0.4	0.47	0.47	0.3	0.47
Supercharger PR	4.25	4.25	4.25	4.25	4.25
Supercharger Efficiency	0.85	0.85	0.85	0.8	0.85
Results of simulation					
Internal EGR	0.311	0.163	0.263	0.302	0.188
SFC, g/kWh	0.283	0.256	0.248	0.261	0.247
Max. cylinder pressure, bar	67.7	196	180	95	199
Max. cylinder temperature, bar	1639	1803	1810	1923	1748
Ringing intensity,	0.353	1.68	4.33	1.47	5.12
NOx, g/kWh	1.06	1.23	0.53	0.737	0.393
Bosch smoke number	0.855	0.766	0.227	0.898	1
PM, g/kWh	0.254	0.135	0.0316	0.179	0.186
Air/Fuel equivalence ratio	2.67	1.51	1.74	1.765	1.747
Start of injection	7.4	0.2	5	9	10.6
Total engine power, kW	3.17	37.17	18.8	8.97	59.5
Supercharger power, kW	1.44	10.85	5.57	2.87	16.8
Superch. pow./Pist. eng. pow.	0.312	0.226	0.229	0.242	0.22
Residual Gas Mass Fraction x_r	0.311	0.163	0.263	0.302	0.306

Detail tables of the z-engine simulation results are presented in the tables 3 - 7.

Table 3

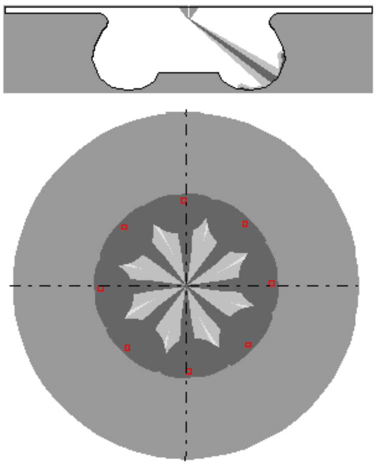
Z-engine simulation data at: BMEP=3.3 @ 1000 RPM (Case #1)

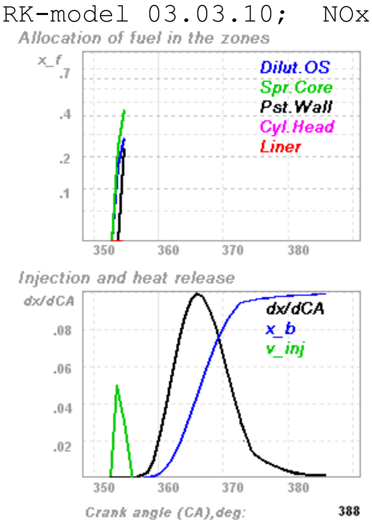
```
2010-05-13 08-33-40 Z-engine
 Case: #1 :: Very small load;
 Title: Intake dur=11 Theta=6
 www.diesel-rk.bmstu.ru
  Fuel:      Diesel No. 2

   ---- PARAMETERS OF ENGINE WITH TURBOCOMPAUNDING OR SUPERCHARGING ----
   3.1744      - P_ovrl   - Overall Power in view of geared T/C/TC, kW
  -1.4409      - dP_add   - Power added by geared Turb/Comp/TC, kW
   30.316      - Torq_ovrl- Overall Torque in view of geared T/C/TC, N m
   3.3414      - BMEP_ovrl- Overall BMEP, bar
  0.28352      - SFC_ovrl - Overall Specific Fuel Consumption, kg/kWh
  0.29877      - Eta_ovrl - Overall Engine Efficiency
   10.000      - R_gear   - Gear ratio of TK speed reducer
  0.95000      - Eta_mC.hp- Mechanical Efficiency of HPC
  -1.4409      - dPdrv_hp - Power added by geared Unit of HP stage, kW
   10.000      - R_gear.lp- Gear Ratio of LP Units and drive shaft coupling
  0.95000      - Eta_mC.lp- Mechanical Efficiency of LP Compressor
 -0.53095E-05 - dPdrv_lp - Power added by geared Unit of LP stage, kW

   ----------------- PARAMETERS OF EFFICIENCY AND POWER ----------------
   1000.0      - RPM      - Engine Speed, rev/min
   4.6153      - P_eng    - Piston Engine Power, kW
   4.8582      - BMEP     - Brake Mean Effective Pressure, bar
   44.076      - Torque   - Brake Torque, N m
  0.00750      - m_f      - Mass of Fuel Supplied per cycle, g
  0.19500      - SFC      - Specific Fuel Consumption, kg/kWh
  0.43438      - Eta_f    - Efficiency of piston engine
   5.5224      - IMEP     - Indicated Mean Effective Pressure, bar
  0.49377      - Eta_i    - Indicated Efficiency
  0.66420      - FMEP     - Friction Mean Effective Pressure, bar (Intern.Exp)
  0.87973      - Eta_m    - Mechanical Efficiency of Piston Engine

   --------------------- ENVIRONMENTAL PARAMETERS ----------------------
   1.0000      - p_sea    - Static Atmospheric Pressure on sea level, bar
   298.00      - T_sea    - Static Atmospheric Temperature on sea level, K
   0.0000      - A_ab.sea - Altitude Above Sea Level, km
   0.0000      - v_flight - Velosity of Flight, km/h (for aircraft engine)
   1.0000      - p_amb    - Static Ambient Pressure, bar
   298.00      - T_amb    - Static Ambient Temperature, K
   1.0000      - po_amb   - Total Ambient Pressure, bar
   298.00      - To_amb   - Total Ambient Temperature, K
   1.0050      - p_Te     - Exhaust Back Pressure, bar (after turbine)
  0.99800      - po_afltr - Total Pressure after Induction Air Filter, bar

   ------------------ TURBOCHARGING AND GAS EXCHANGE -------------------
   4.1789      - p_C      - Pressure before Inlet Manifold, bar
   315.98      - T_C      - Temperature before Inlet Manifold, K
  0.00758      - m_air    - Total Mass Airflow (+EGR) of Piston Engine, kg/s
  0.81705      - Eta_TC   - Turbocharger Efficiency
   1.0373      - po_T     - Average Total Turbine Inlet Pressure, bar
   601.65      - To_T     - Average Total Turbine Inlet Temperature, K
  0.00792      - m_gas    - Mass Exhaust Gasflow of Pison Engine, g/s
   2.0930      - A/F_eq.t - Total Air Fuel Equivalence Ratio (Lambda)
  0.47779      - F/A_eq.t - Total Fuel Air Equivalence Ratio
  0.21538      - Eta_v    - Volumetric Efficiency
  0.31059      - x_r      - Residual Gas Mass Fraction
  0.80383      - Phi      - Coeff. of Scavenging (Delivery Ratio / Eta_v)
   0.0000      - BF_int   - Burnt Gas Fraction Backflowed into the Intake, %
   2.1714      - %Blow-by - % of Blow-by through piston rings
```

```
 --------------------------- INTAKE SYSTEM ---------------------------
 4.1769     - p_int    - Average Intake Manifold Pressure, bar
 287.98     - T_int    - Average Intake Manifold Temperature, K
0.76426     - v_int    - Average Gas Velocity in intake manifold, m/s
 290.98     - Tw_int   - Average Intake Manifold Wall Temperature, K
 79.481     - hc_int   - Heat Transfer Coeff. in Intake Manifold, W/(m2*K)
 183.13     - hc_int.p - Heat Transfer Coeff. in Intake Port, W/(m2*K)

 -------------------------- EXHAUST SYSTEM ---------------------------
0.99228     - p_exh    - Average Exhaust Manifold Gas Pressure, bar
 541.85     - T_exh    - Average Exhaust Manifold Gas Temperature, K
 6.3540     - v_exh    - Average Gas Velocity in exhaust manifold, m/s
 124.03     - Sh       - Strouhal number: Sh=a*Tau/L (has to be: Sh > 8)
 470.58     - Tw_exh   - Average Exhaust Manifold Wall Temperature, K
 91.790     - hc_exh   - Heat Transfer Coeff. in Exhaust Manifold, W/(m2*K)
 103.99     - hc_exh.p - Heat Transfer Coeff. in Exhaust Port, W/(m2*K)

 ---------------------------- COMBUSTION -----------------------------
 2.6672     - A/F_eq   - Air Fiel Equival. Ratio (Lambda) in the Cylinder
0.37493     - F/A_eq   - Fuel Air Equivalence Ratio in the Cylinder
 67.701     - p_max    - Maximum Cylinder Pressure, bar
 1639.0     - T_max    - Maximum Cylinder Temperature, K
 11.000     - CA_p.max - Angle of Max. Cylinder Pressure, deg. A.TDC
 14.000     - CA_t.max - Angle of Max. Cylinder Temperature, deg. A.TDC
 3.0103     - dp/dTheta- Max. Rate of Pressure Rise, bar/deg.
0.35290     - Ring_Intn- Ringing / Knock Intensity, MW/m2
Injection: Common Rail
 648.44     - p_inj.max- Max. Injection Pres. (before nozzles), bar
 13.281     - d_32     - Sauter Mean Diameter of Drops, microns
 7.4000     - SOI      - Start Of Injection or Ignition Timing, deg. B.TDC
 2.2000     - Phi_inj  - Duration of Injection, CA deg.
 6.4220     - Phi_ign  - Ignition Delay Period, deg.
            -   ...    - Integral  calc. by CHEMKIN for Dies. Oil:   6.4
0.97797     - SOC      - Start of Combustion, deg. B.TDC
0.99000     - x_e.id   - Fuel Mass Fraction Evaporated during Ignit. Delay
 35.600     - Phi_z    - Combustion duration, deg.
 4.7425     - Rs_tdc   - Swirl Ratio in the Combustion Chamber at TDC
 1.7588     - Rs_ivc   - Swirl Ratio in the Cylinder at IVC
 9.2837     - W_swirl  - Max. Air Swirl Velocity, m/s  at cylinder R=   19

 ------------------------ ECOLOGICAL PARAMETERS ----------------------
 7.7941     - Hartridge- Hartridge Smoke Level
0.85535     - Bosch    - Bosch Smoke Number
0.18985     - K.m-1    - Factor of Absolute Light Absorption, 1/m
0.25414     - PM       - Specific Particulate Matter, g/kWh
 913.56     - CO2      - Specific Carbon dioxide emission, g/kWh
 162.35     - NOx.dry  - Fraction of dry NOx in exh. gas, ppm
 1.0577     - NO       - Specif. NOx emiss. reduc. to NO, g/kWh(DKM)
0.99822     - SE       - Summary emission of PM and NOx
 0.0000     - SO2      - Specific SO2 emission, g/kWh

 ------------------------- CYLINDER PARAMETERS -----------------------
 5.2934     - p_ivc    - Pressure at IVC, bar
 543.58     - T_ivc    - Temperature at IVC, K
 47.273     - p_tdc    - Compression Pressure (at TDC), bar
 961.77     - T_tdc    - Compression Temperature (at TDC), K
 3.1942     - p_evo    - Pressure at EVO, bar
 761.59     - T_evo    - Temperaure at EVO, K

 ------------------ HEAT EXCHANGE IN THE CYLINDER --------------------
 1130.8     - T_eq     - Average Equivalent Temperature of Cycle, K
 233.66     - hc_c     - Aver. Factor of Heat Transfer in Cyl., W/m2/K
 800.00     - Tw_pist  - Average Piston Crown Temperature, K
```

```
 440.00     - Tw_liner - Average Cylinder Liner Temperature, K
 700.00     - Tw_head  - Average Head Wall Temperature, K
 372.94     - Tw_cool  - Average Temperature of Cooled Surface
                 head    of Cylinder Head, K
 398.16     - Tboil    - Boiling Temp. in Liquid Cooling System, K
 7994.9     - hc_cool  - Average Factor of Heat Transfer, W/(m2*K)
                         from head cooled surface to coolant
 409.85     - q_head   - Heat Flow in a Cylinder Head, J/s
 314.71     - q_pist   - Heat Flow in a Piston Crown, J/s
 245.02     - q_liner  - Heat Flow in a Cylinder Liner, J/s

 --------------- MAIN ENGINE CONSTRUCTION PARAMETERS -----------------
 15.500     - CR       - Compression Ratio
 5.0765     - CR_opn.h - CR in view of losses due to open height of porting
 8.0000     - n_inj    - Number of Injector Nozzles
0.13100     - d_inj    - Injector Nozzles Bore, mm
 2.2000     - Phi_inj  - Injection Duration for spec. Inject. Profile, deg.
 0.0000     - m_f_ip   - Fuel Mass for specified Injection Profile, g
-112.00     - IVO      - Intake Valve Opening, deg. before DC
 123.00     - IVC      - Intake Valve Closing, deg. after BDC
 68.000     - EVO      - Exhaust Valve Opening, deg. before BDC
 112.00     - EVC      - Exhaust Valve Closing, deg. after  DC

 ----------------- COMPRESSOR PARAMETERS  LP stage -------------------
 10000.     - RPM_C.lp - Rotor Speed of LPC, rev/min
0.01616     - P_C.lp   - Power of LP Compressor, kW
0.40000     - Eta_C.lp - Adiabatic Efficiency of LP Compressor
0.00758     - m_C.lp   - Mass Airflow of LP Compressor, kg/sec
0.13117     - m*_C.lp  - Mass Airflow Parameter, kg SQRT(K)/(s bar)
0.00760     - m.cor_Clp- Corrected Mass Airflow of LPC, kg/s
 579.28     - RPM*_C.lp- Rotor Speed Parameter, rev/min SQRT(K)
 10000.     - RPMcor_lp- Corrected Rotor Speed, rev/min
 1.0100     - PR_C.lp  - Pressure Ratio of LP Compressor
 0.0000     - Kpi_C.lp - Factor Kpi of LP Compressor
0.99800     - po_iC.lp - Inlet Total Pressure of LPC, bar
 298.00     - To_iC.lp - Inlet Total Temperature of LPC, K
 1.0080     - po_"C.lp - Total Discharge Press.(before LP cooler), bar
 300.12     - To_"C.lp - Total Discharge Temp. (before LP cooler), K
0.90000     - Ecool.lp - Thermal Efficiency of LP Air Inter-cooler
 298.00     - Tcool.lp - LP Inter-cooler Refrigerant Temperature, K
0.98798     - po_C.lp  - Total Pressure after LP Inter-cooler, bar
 298.21     - To_C.lp  - Total Temperature after LP Inter-cooler, K

 ----------------- COMPRESSOR PARAMETERS  HP stage -------------------
 10000.     - RPM_C.hp - Rotor Speed of HPC, rev/min
 1.3689     - P_C.hp   - Power of HPC, kW
0.85000     - Eta_C.hp - Adiabatic Efficiency of HPC
0.00758     - m_C.hp   - Mass Airflow of HP Compressor, kg/s
0.13255     - m*_C.hp  - Mass Airflow Parameter, kg SQRT(K)/(s bar)
0.00768     - m.cor_Chp- Corrected Mass Airflow of HPC, kg/s
 579.08     - RPM*_C.hp- Rotor Speed Parameter, rev/min SQRT(K)
 9996.4     - RPMcor_hp- Corrected Rotor Speed, rev/min
 4.2500     - PR_C.hp  - Pressure Ratio of HP Compressor
 0.0000     - Kpi_C.hp - Factor Kpi of HP Compressor
0.98798     - po_iC.hp - Inlet Total Pressure of HPC, bar
 298.21     - To_iC.hp - Inlet Total Temperature of HPC, K
 4.1989     - po_"C.hp - Total Discharge Press. (before HP cooler), bar
 477.82     - To_"C.hp - Total Discharge Temp. (before HP cooler), K
0.90000     - Ecool.hp - Thermal Efficiency of HP Air Inter-cooler
 298.00     - Tcool.hp - HP Inter-cooler Refrigerant Temperature, K
 4.1789     - po_C.hp  - Total Pressure after Inter-cooler, bar
 315.98     - To_C.hp  - Total Temperature after Inter-cooler, K
```

```
  ----------------- TURBINE PARAMETERS  HP stage ----------------------
  10000.     - RPM_T.hp - HP Turbine Rotor Speed, rev/min
  0.0000     - P_T.hp   - Effective Power of HPT, kW
  1.0000     - Eta_T.hp - Internal turbine Efficiency of HPT
 0.90900     - Eta_mT.hp- Mechanical Efficiency of HPT
 0.00792     - m_T.hp   - Mass Gasflow of HPT, kg/s
 0.18732     - m*_T.hp  - Mass Gasflow Parameter, kg SQRT(K)/s kPa
  407.69     - RPM*_T.hp- Rotor Speed Parameter, rev/min SQRT(K)
  1.0000     - PR_T.hp  - Expansion Pressure Ratio of HPT
  0.0000     - B_T.hp   - Relative Work B=118.34 {1-PR**[(1-k)/k]} Eta_T
  1.0373     - po_T.hp  - Inlet Total Pressure of HPT, bar
  601.65     - To_T.hp  - Inlet Total Temperature of HPT, K
  1.0373     - po_eT.hp - HP Turbine Exhaust Back Pressure, bar
  601.65     - To_eT.hp - HP Turbine Exhaust Back Temperature, K

  ----------------- TURBINE PARAMETERS  LP stage ----------------------
  10000.     - RPM_T.lp - LP Turbine Rotor Speed, rev/min
 0.01616     - P_T.lp   - Effective Power of LPT, kW
 0.44004     - Eta_T.lp - Adiabatic Efficiency of LPT
 0.90900     - Eta_mT.lp- Mechanical Efficiency  of LPT
 0.00792     - m_T.lp   - Mass Gasflow of LPT, kg/s
 0.18732     - m*_T.lp  - Mass Gasflow Parameter, kg SQRT(K)/s kPa
  407.69     - RPM*_T.lp- Rotor Speed Parameter, rev/min SQRT(K)
  1.0308     - PR_T.lp  - Expansion Pressure Ratio of LPT
 0.39109     - B_T.lp   - Relative Work B=118.34 {1-PR**[(1-k)/k]} Eta_T
  1.0373     - po_T.lp  - Inlet Total Pressure of LPT, bar
  601.65     - To_T.lp  - Inlet Total Temperature of LPT, K
  1.0062     - po_eT.lp - LP Turbine Exhaust Back Pressure, bar
  599.66     - To_eT.lp - LP 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 ¦ 54.0 ¦pist. bowl¦ 44.41  19.93   35.66    6.68    0.00   0.00
-------------------------------------------------------------------------
Sum of all sprays    %  93.¦ 25.09  42.23   26.10    0.00    0.00   0.00
=========================================================================
Evaporation constants  bi  ¦****** 529020  ******  ******  ******  18725
=========================================================================
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:20.45
   Ratio¦  Rs of piston bowl     4.74 ¦   Rs  ¦-by Razleytsev    : 4.51
____________________
Versions:     Kernel 20.03.10;  RK-model 03.03.10;  NOx-model 02.04.10
```





Injection and HRR

Table 4

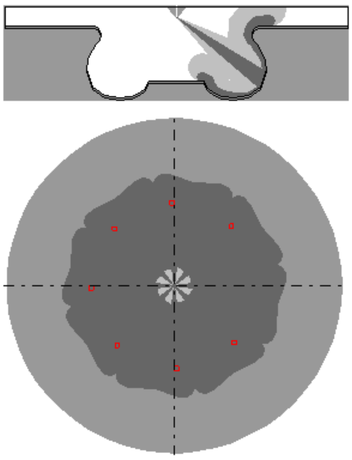
Z-engine simulation data at: BMEP=26.1 @ 1500 RPM (Case #2)

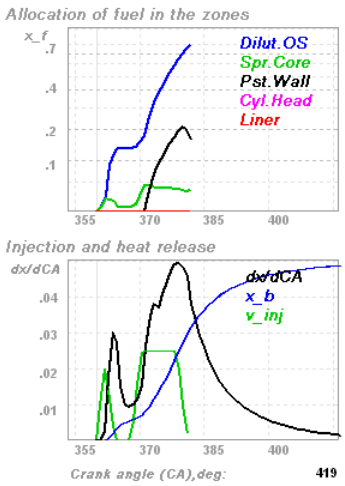
```
Mode: #9 :: Max Torque Double inj BMEP=26  Alpha=54;
 Title: Intake dur=16   www.diesel-rk.bmstu.ru    Fuel: Diesel No. 2

  ---- PARAMETERS OF ENGINE WITH TURBOCOMPAUNDING OR SUPERCHARGING ----
  37.172      - P_ovrl    - Overall Power in view of geared T/C/TC, kW
 -10.853      - dP_add    - Power added by geared Turb/Comp/TC, kW
  236.66      - Torq_ovrl- Overall Torque in view of geared T/C/TC, N m
  26.085      - BMEP_ovrl- Overall BMEP, bar
 0.25665      - SFC_ovrl - Overall Specific Fuel Consumption, kg/kWh
 0.33005      - Eta_ovrl - Overall Engine Efficiency
  10.000      - R_gear    - Gear ratio of TK speed reducer
 0.95000      - Eta_mC.hp- Mechanical Efficiency of HPC
 -10.858      - dPdrv_hp - Power added by geared Unit of HP stage, kW
  10.000      - R_gear.lp- Gear Ratio of LP Units and drive shaft coupling
 0.95000      - Eta_mC.lp- Mechanical Efficiency of LP Compressor
 0.00501      - dPdrv_lp - Power added by geared Unit of LP stage, kW

  ----------------- PARAMETERS OF EFFICIENCY AND POWER ----------------
  1500.0      - RPM       - Engine Speed, rev/min
  48.025      - P_eng     - Piston Engine Power, kW
  33.701      - BMEP      - Brake Mean Effective Pressure, bar
  305.76      - Torque    - Brake Torque, N m
 0.05300      - m_f       - Mass of Fuel Supplied per cycle, g
 0.19865      - SFC       - Specific Fuel Consumption, kg/kWh
 0.42641      - Eta_f     - Efficiency of piston engine
  36.162      - IMEP      - Indicated Mean Effective Pressure, bar
 0.45756      - Eta_i     - Indicated Efficiency
  2.4612      - FMEP      - Friction Mean Effective Pressure, bar (Intern.Exp)
 0.93194      - Eta_m     - Mechanical Efficiency of Piston Engine

  --------------------- ENVIRONMENTAL PARAMETERS ----------------------
  1.0000      - p_sea     - Static Atmospheric Pressure on sea level, bar
  298.00      - T_sea     - Static Atmospheric Temperature on sea level, K
  0.0000      - A_ab.sea - Altitude Above Sea Level, km
  0.0000      - v_flight - Velosity of Flight, km/h (for aircraft engine)
  1.0000      - p_amb     - Static Ambient Pressure, bar
  298.00      - T_amb     - Static Ambient Temperature, K
  1.0000      - po_amb    - Total Ambient Pressure, bar
  298.00      - 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 -------------------
  17.987      - p_C       - Pressure before Inlet Manifold, bar
  319.47      - T_C       - Temperature before Inlet Manifold, K
 0.05325      - m_air     - Total Mass Airflow (+EGR) of Piston Engine, kg/s
 0.73836      - Eta_TC    - Turbocharger Efficiency
  4.1212      - po_T      - Average Total Turbine Inlet Pressure, bar
  942.34      - To_T      - Average Total Turbine Inlet Temperature, K
 0.05641      - m_gas     - Mass Exhaust Gasflow of Pison Engine, g/s
  1.3866      - A/F_eq.t - Total Air Fuel Equivalence Ratio (Lambda)
 0.72121      - F/A_eq.t - Total Fuel Air Equivalence Ratio
 0.20256      - Eta_v     - Volumetric Efficiency
 0.16297      - x_r       - Residual Gas Mass Fraction
 0.94085      - Phi       - Coeff. of Scavenging (Delivery Ratio / Eta_v)
  0.0000      - BF_int    - Burnt Gas Fraction Backflowed into the Intake, %
  1.2213      - %Blow-by - % of Blow-by through piston rings

  --------------------------- INTAKE SYSTEM ---------------------------
  17.959      - p_int     - Average Intake Manifold Pressure, bar
```

```
 313.66     - T_int    - Average Intake Manifold Temperature, K
 1.3606     - v_int    - Average Gas Velocity in intake manifold, m/s
 316.67     - Tw_int   - Average Intake Manifold Wall Temperature, K
 194.35     - hc_int   - Heat Transfer Coeff. in Intake Manifold, W/(m2*K)
 168.36     - hc_int.p - Heat Transfer Coeff. in Intake Port, W/(m2*K)

 -------------------------- EXHAUST SYSTEM --------------------------
 4.0145     - p_exh    - Average Exhaust Manifold Gas Pressure, bar
 941.27     - T_exh    - Average Exhaust Manifold Gas Temperature, K
 19.699     - v_exh    - Average Gas Velocity in exhaust manifold, m/s
 108.98     - Sh       - Strouhal number: Sh=a*Tau/L (has to be: Sh > 8)
 743.68     - Tw_exh   - Average Exhaust Manifold Wall Temperature, K
 120.95     - hc_exh   - Heat Transfer Coeff. in Exhaust Manifold, W/(m2*K)
 181.75     - hc_exh.p - Heat Transfer Coeff. in Exhaust Port, W/(m2*K)

 ---------------------------- COMBUSTION ----------------------------
 1.5135     - A/F_eq   - Air Fiel Equival. Ratio (Lambda) in the Cylinder
0.66073     - F/A_eq   - Fuel Air Equivalence Ratio in the Cylinder
 196.10     - p_max    - Maximum Cylinder Pressure, bar
 1803.5     - T_max    - Maximum Cylinder Temperature, K
 6.0000     - CA_p.max - Angle of Max. Cylinder Pressure, deg. A.TDC
 31.000     - CA_t.max - Angle of Max. Cylinder Temperature, deg. A.TDC
 7.2757     - dp/dTheta- Max. Rate of Pressure Rise, bar/deg.
 1.6798     - Ring_Intn- Ringing / Knock Intensity, MW/m2
Injection: Common Rail
 1394.2     - p_inj.max- Max. Injection Pres. (before nozzles), bar
 8.4095     - d_32     - Sauter Mean Diameter of Drops, microns
0.20000     - SOI      - Start Of Injection or Ignition Timing, deg. B.TDC
 22.000     - Phi_inj  - Duration of Injection, CA deg.
 1.2431     - Phi_ign  - Ignition Delay Period, deg.
            -   ...    - Integral  calc. by CHEMKIN for Dies. Oil:   1.2
-1.0431     - SOC      - Start of Combustion, deg. B.TDC
0.01149     - x_e.id   - Fuel Mass Fraction Evaporated during Ignit. Delay
 83.050     - Phi_z    - Combustion duration, deg.
 4.7171     - Rs_tdc   - Swirl Ratio in the Combustion Chamber at TDC
 1.6000     - Rs_ivc   - Swirl Ratio in the Cylinder at IVC
 13.851     - W_swirl  - Max. Air Swirl Velocity, m/s  at cylinder R=   19

 ------------------------ ECOLOGICAL PARAMETERS ----------------------
 6.9857     - Hartridge- Hartridge Smoke Level
0.76643     - Bosch    - Bosch Smoke Number
0.16964     - K.m-1    - Factor of Absolute Light Absorption, 1/m
0.13461     - PM       - Specific Particulate Matter, g/kWh
 826.97     - CO2      - Specific Carbon dioxide emission, g/kWh
 394.00     - NOx.dry  - Fraction of dry NOx in exh. gas, ppm
 1.2371     - NO       - Specif. NOx emiss. reduc. to NO, g/kWh(DKM)
0.62543     - SE       - Summary emission of PM and NOx
 0.0000     - SO2      - Specific SO2 emission, g/kWh

 ------------------------- CYLINDER PARAMETERS -----------------------
 23.613     - p_ivc    - Pressure at IVC, bar
 552.14     - T_ivc    - Temperature at IVC, K
 178.88     - p_tdc    - Compression Pressure (at TDC), bar
 939.03     - T_tdc    - Compression Temperature (at TDC), K
 20.404     - p_evo    - Pressure at EVO, bar
 1232.0     - T_evo    - Temperaure at EVO, K

 ------------------ HEAT EXCHANGE IN THE CYLINDER --------------------
 1256.7     - T_eq     - Average Equivalent Temperature of Cycle, K
 863.98     - hc_c     - Aver. Factor of Heat Transfer in Cyl., W/m2/K
 800.00     - Tw_pist  - Average Piston Crown Temperature, K
 440.00     - Tw_liner - Average Cylinder Liner Temperature, K
 700.00     - Tw_head  - Average Head Wall Temperature, K
 398.64     - Tw_cool  - Average Temperature of Cooled Surface
```

```
                 head    of Cylinder Head, K
 398.16     - Tboil    - Boiling Temp. in Liquid Cooling System, K
 12519.     - hc_cool  - Average Factor of Heat Transfer, W/(m2*K)
                         from head cooled surface to coolant
 1958.2     - q_head   - Heat Flow in a Cylinder Head, J/s
 1606.5     - q_pist   - Heat Flow in a Piston Crown, J/s
 2344.8     - q_liner  - Heat Flow in a Cylinder Liner, J/s

 --------------- MAIN ENGINE CONSTRUCTION PARAMETERS -----------------
 15.500     - CR       - Compression Ratio
 4.4708     - CR_opn.h - CR in view of losses due to open height of porting
 8.0000     - n_inj    - Number of Injector Nozzles
0.13100     - d_inj    - Injector Nozzles Bore, mm
 22.000     - Phi_inj  - Injection Duration for spec. Inject. Profile, deg.
 0.0000     - m_f_ip   - Fuel Mass for specified Injection Profile, g
-112.00     - IVO      - Intake Valve Opening, deg. before DC
 128.00     - IVC      - Intake Valve Closing, deg. after BDC
 68.000     - EVO      - Exhaust Valve Opening, deg. before BDC
 112.00     - EVC      - Exhaust Valve Closing, deg. after  DC

 ----------------- COMPRESSOR PARAMETERS  LP stage -------------------
 15000.     - RPM_C.lp - Rotor Speed of LPC, rev/min
 11.780     - P_C.lp   - Power of LP Compressor, kW
0.70000     - Eta_C.lp - Adiabatic Efficiency of LP Compressor
0.05325     - m_C.lp   - Mass Airflow of LP Compressor, kg/sec
0.92858     - m*_C.lp  - Mass Airflow Parameter, kg SQRT(K)/(s bar)
0.05379     - m.cor_Clp- Corrected Mass Airflow of LPC, kg/s
 868.93     - RPM*_C.lp- Rotor Speed Parameter, rev/min SQRT(K)
 15000.     - RPMcor_lp- Corrected Rotor Speed, rev/min
 4.3000     - PR_C.lp  - Pressure Ratio of LP Compressor
 0.0000     - Kpi_C.lp - Factor Kpi of LP Compressor
0.99000     - po_iC.lp - Inlet Total Pressure of LPC, bar
 298.00     - To_iC.lp - Inlet Total Temperature of LPC, K
 4.2570     - po_"C.lp - Total Discharge Press.(before LP cooler), bar
 518.10     - To_"C.lp - Total Discharge Temp. (before LP cooler), K
0.90000     - Ecool.lp - Thermal Efficiency of LP Air Inter-cooler
 298.00     - Tcool.lp - LP Inter-cooler Refrigerant Temperature, K
 4.2370     - po_C.lp  - Total Pressure after LP Inter-cooler, bar
 320.01     - To_C.lp  - Total Temperature after LP Inter-cooler, K

 ----------------- COMPRESSOR PARAMETERS  HP stage -------------------
 15000.     - RPM_C.hp - Rotor Speed of HPC, rev/min
 10.315     - P_C.hp   - Power of HPC, kW
0.85000     - Eta_C.hp - Adiabatic Efficiency of HPC
0.05325     - m_C.hp   - Mass Airflow of HP Compressor, kg/s
0.22484     - m*_C.hp  - Mass Airflow Parameter, kg SQRT(K)/(s bar)
0.01302     - m.cor_Chp- Corrected Mass Airflow of HPC, kg/s
 838.51     - RPM*_C.hp- Rotor Speed Parameter, rev/min SQRT(K)
 14475.     - RPMcor_hp- Corrected Rotor Speed, rev/min
 4.2500     - PR_C.hp  - Pressure Ratio of HP Compressor
 0.0000     - Kpi_C.hp - Factor Kpi of HP Compressor
 4.2370     - po_iC.hp - Inlet Total Pressure of HPC, bar
 320.01     - To_iC.hp - Inlet Total Temperature of HPC, K
 18.007     - po_"C.hp - Total Discharge Press. (before HP cooler), bar
 512.75     - To_"C.hp - Total Discharge Temp. (before HP cooler), K
0.90000     - Ecool.hp - Thermal Efficiency of HP Air Inter-cooler
 298.00     - Tcool.hp - HP Inter-cooler Refrigerant Temperature, K
 17.987     - po_C.hp  - Total Pressure after Inter-cooler, bar
 319.47     - To_C.hp  - Total Temperature after Inter-cooler, K

 ----------------- TURBINE PARAMETERS  HP stage ----------------------
 15000.     - RPM_T.hp - HP Turbine Rotor Speed, rev/min
 0.0000     - P_T.hp   - Effective Power of HPT, kW
 1.0000     - Eta_T.hp - Internal turbine Efficiency of HPT
```

```
  0.90900     - Eta_mT.hp- Mechanical Efficiency of HPT
  0.05641     - m_T.hp   - Mass Gasflow of HPT, kg/s
  0.42017     - m*_T.hp  - Mass Gasflow Parameter, kg SQRT(K)/s kPa
   488.64     - RPM*_T.hp- Rotor Speed Parameter, rev/min SQRT(K)
   1.0000     - PR_T.hp  - Expansion Pressure Ratio of HPT
   0.0000     - B_T.hp   - Relative Work B=118.34 {1-PR**[(1-k)/k]} Eta_T
   4.1212     - po_T.hp  - Inlet Total Pressure of HPT, bar
   942.34     - To_T.hp  - Inlet Total Temperature of HPT, K
   4.1212     - po_eT.hp - HP Turbine Exhaust Back Pressure, bar
   942.34     - To_eT.hp - HP Turbine Exhaust Back Temperature, K

   ----------------- TURBINE PARAMETERS  LP stage ----------------------
   15000.     - RPM_T.lp - LP Turbine Rotor Speed, rev/min
   11.785     - P_T.lp   - Effective Power of LPT, kW
  0.73865     - Eta_T.lp - Adiabatic Efficiency of LPT
  0.90900     - Eta_mT.lp- Mechanical Efficiency  of LPT
  0.05641     - m_T.lp   - Mass Gasflow of LPT, kg/s
  0.42017     - m*_T.lp  - Mass Gasflow Parameter, kg SQRT(K)/s kPa
   488.64     - RPM*_T.lp- Rotor Speed Parameter, rev/min SQRT(K)
   4.0342     - PR_T.lp  - Expansion Pressure Ratio of LPT
   25.572     - B_T.lp   - Relative Work B=118.34 {1-PR**[(1-k)/k]} Eta_T
   4.1212     - po_T.lp  - Inlet Total Pressure of LPT, bar
   942.34     - To_T.lp  - Inlet Total Temperature of LPT, K
   1.0216     - po_eT.lp - LP Turbine Exhaust Back Pressure, bar
   729.77     - To_eT.lp - LP Turbine Exhaust Back Temperature, K

  ------------------ MULTIPLE INJECTION PARAMETERS ---------------------
          SOI  Fraction  Mass   Separ.  Duration   d32  Ign.Delay  Burst
       [CA BTDC]          [g]    [CA]     [CA]  [micron]   [CA]    [CA]
Pilot 1    0.2   0.150  0.0079   ----    4.500    10.45    1.24    361.0
Main      -8.0   0.850  0.0451   3.750  13.750     8.05    0.96    369.0

      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 ¦ 54.0 ¦pist. bowl¦ 80.63   0.00   19.37   19.11    0.00   0.00
------------------------------------------------------------------------
Sum of all sprays    % 100.¦ 68.55   3.42    1.97   25.82    0.00   0.00
========================================================================
Evaporation constants  bi  ¦ 35008  15398   21638   18284   17046    130
========================================================================
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: 2.05
   Ratio¦  Rs of piston bowl     4.72 ¦   Rs  ¦-by Razleytsev    : 2.05
Versions:     Kernel 20.03.10;  RK-model 03.03.10;  NOx-model 02.04.10
```





Injection and HRR

Table 5

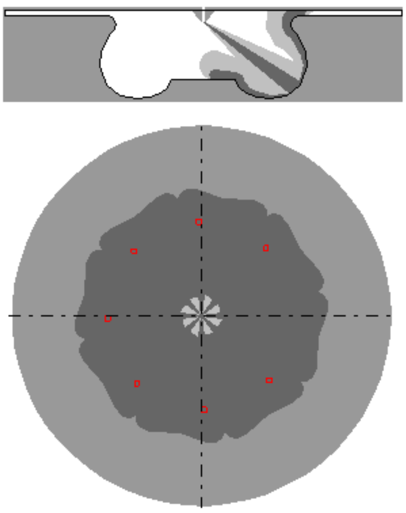
Z-engine simulation data at: BMEP=13.2 @ 1500 RPM (Case #3)

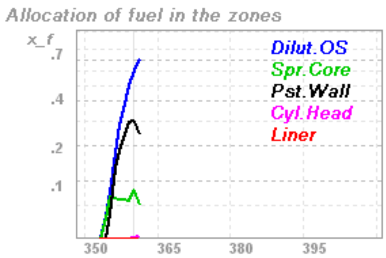
```
2010-05-02 22-10-16 Z-engine
 Mode: #8  : RPM=1500, BMEP=14.5;
www.diesel-rk.bmstu.ru
  Fuel:      Diesel No. 2

   ---- PARAMETERS OF ENGINE WITH TURBOCOMPAUNDING OR SUPERCHARGING ----
   18.827     - P_ovrl   - Overall Power in view of geared T/C/TC, kW
  -5.5745     - dP_add   - Power added by geared Turb/Comp/TC, kW
   119.87     - Torq_ovrl- Overall Torque in view of geared T/C/TC, N m
   13.212     - BMEP_ovrl- Overall BMEP, bar
  0.24858     - SFC_ovrl - Overall Specific Fuel Consumption, kg/kWh
  0.34076     - Eta_ovrl - Overall Engine Efficiency
   10.000     - R_gear   - Gear ratio of TK speed reducer
  0.95000     - Eta_mC.hp- Mechanical Efficiency of HPC
  -5.5819     - dPdrv_hp - Power added by geared Unit of HP stage, kW
   10.000     - R_gear.lp- Gear Ratio of LP Units and drive shaft coupling
  0.95000     - Eta_mC.lp- Mechanical Efficiency of LP Compressor
  0.00748     - dPdrv_lp - Power added by geared Unit of LP stage, kW

   ----------------- PARAMETERS OF EFFICIENCY AND POWER ----------------
   1500.0     - RPM      - Engine Speed, rev/min
   24.402     - P_eng    - Piston Engine Power, kW
   17.124     - BMEP     - Brake Mean Effective Pressure, bar
   155.36     - Torque   - Brake Torque, N m
  0.02600     - m_f      - Mass of Fuel Supplied per cycle, g
  0.19179     - SFC      - Specific Fuel Consumption, kg/kWh
  0.44166     - Eta_f    - Efficiency of piston engine
   18.750     - IMEP     - Indicated Mean Effective Pressure, bar
  0.48360     - Eta_i    - Indicated Efficiency
   1.6263     - FMEP     - Friction Mean Effective Pressure, bar (Intern.Exp)
  0.91326     - Eta_m    - Mechanical Efficiency of Piston Engine

   --------------------- ENVIRONMENTAL PARAMETERS ----------------------
   1.0000     - p_sea    - Static Atmospheric Pressure on sea level, bar
   298.00     - T_sea    - Static Atmospheric Temperature on sea level, K
   0.0000     - A_ab.sea - Altitude Above Sea Level, km
   0.0000     - v_flight - Velosity of Flight, km/h (for aircraft engine)
   1.0000     - p_amb    - Static Ambient Pressure, bar
   298.00     - T_amb    - Static Ambient Temperature, K
   1.0000     - po_amb   - Total Ambient Pressure, bar
   298.00     - 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 -------------------
   10.834     - p_C      - Pressure before Inlet Manifold, bar
   318.09     - T_C      - Temperature before Inlet Manifold, K
  0.02814     - m_air    - Total Mass Airflow (+EGR) of Piston Engine, kg/s
  0.73982     - Eta_TC   - Turbocharger Efficiency
   2.8618     - po_T     - Average Total Turbine Inlet Pressure, bar
   770.81     - To_T     - Average Total Turbine Inlet Temperature, K
  0.03000     - m_gas    - Mass Exhaust Gasflow of Pison Engine, g/s
   1.4934     - A/F_eq.t - Total Air Fuel Equivalence Ratio (Lambda)
  0.66963     - F/A_eq.t - Total Fuel Air Equivalence Ratio
  0.18870     - Eta_v    - Volumetric Efficiency
  0.26291     - x_r      - Residual Gas Mass Fraction
  0.88188     - Phi      - Coeff. of Scavenging (Delivery Ratio / Eta_v)
   0.0000     - BF_int   - Burnt Gas Fraction Backflowed into the Intake, %
   1.4328     - %Blow-by - % of Blow-by through piston rings
```

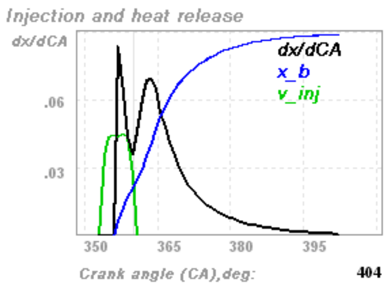
```
 ---------------------------- INTAKE SYSTEM ----------------------------
 10.821     - p_int    - Average Intake Manifold Pressure, bar
 311.74     - T_int    - Average Intake Manifold Temperature, K
 1.1877     - v_int    - Average Gas Velocity in intake manifold, m/s
 311.75     - Tw_int   - Average Intake Manifold Wall Temperature, K
 208.81     - hc_int   - Heat Transfer Coeff. in Intake Manifold, W/(m2*K)
 60.000     - hc_int.p - Heat Transfer Coeff. in Intake Port, W/(m2*K)

 --------------------------- EXHAUST SYSTEM ---------------------------
 2.8227     - p_exh    - Average Exhaust Manifold Gas Pressure, bar
 759.00     - T_exh    - Average Exhaust Manifold Gas Temperature, K
 11.758     - v_exh    - Average Gas Velocity in exhaust manifold, m/s
 97.865     - Sh       - Strouhal number: Sh=a*Tau/L (has to be: Sh > 8)
 602.42     - Tw_exh   - Average Exhaust Manifold Wall Temperature, K
 92.858     - hc_exh   - Heat Transfer Coeff. in Exhaust Manifold, W/(m2*K)
 140.98     - hc_exh.p - Heat Transfer Coeff. in Exhaust Port, W/(m2*K)

 ----------------------------- COMBUSTION -----------------------------
 1.7395     - A/F_eq   - Air Fiel Equival. Ratio (Lambda) in the Cylinder
0.57487     - F/A_eq   - Fuel Air Equivalence Ratio in the Cylinder
 180.23     - p_max    - Maximum Cylinder Pressure, bar
 1810.5     - T_max    - Maximum Cylinder Temperature, K
 9.0000     - CA_p.max - Angle of Max. Cylinder Pressure, deg. A.TDC
 16.000     - CA_t.max - Angle of Max. Cylinder Temperature, deg. A.TDC
 11.193     - dp/dTheta- Max. Rate of Pressure Rise, bar/deg.
 4.3340     - Ring_Intn- Ringing / Knock Intensity, MW/m2
Injection: Injector
 1447.7     - p_inj.max- Max. Injection Pres. (before nozzles), bar
 8.3690     - d_32     - Sauter Mean Diameter of Drops, microns
 5.0000     - SOI      - Start Of Injection or Ignition Timing, deg. B.TDC
 7.5000     - Phi_inj  - Duration of Injection, CA deg.
 2.6682     - Phi_ign  - Ignition Delay Period, deg.
            -   ...    - Integral  calc. by CHEMKIN for Dies. Oil:   2.7
 2.3318     - SOC      - Start of Combustion, deg. B.TDC
0.23151     - x_e.id   - Fuel Mass Fraction Evaporated during Ignit. Delay
 52.800     - Phi_z    - Combustion duration, deg.
 4.3475     - Rs_tdc   - Swirl Ratio in the Combustion Chamber at TDC
 1.6000     - Rs_ivc   - Swirl Ratio in the Cylinder at IVC
 12.765     - W_swirl  - Max. Air Swirl Velocity, m/s  at cylinder R=   19

 ------------------------ ECOLOGICAL PARAMETERS ----------------------
 2.0775     - Hartridge- Hartridge Smoke Level
0.22754     - Bosch    - Bosch Smoke Number
0.04946     - K.m-1    - Factor of Absolute Light Absorption, 1/m
0.03158     - PM       - Specific Particulate Matter, g/kWh
 800.97     - CO2      - Specific Carbon dioxide emission, g/kWh
 142.27     - NOx.dry  - Fraction of dry NOx in exh. gas, ppm
0.53039     - NO       - Specif. NOx emiss. reduc. to NO, g/kWh(DKM)
0.18105     - SE       - Summary emission of PM and NOx
 0.0000     - SO2      - Specific SO2 emission, g/kWh

 ------------------------- CYLINDER PARAMETERS -----------------------
 14.135     - p_ivc    - Pressure at IVC, bar
 565.37     - T_ivc    - Temperature at IVC, K
 110.10     - p_tdc    - Compression Pressure (at TDC), bar
 963.06     - T_tdc    - Compression Temperature (at TDC), K
 9.7001     - p_evo    - Pressure at EVO, bar
 977.98     - T_evo    - Temperaure at EVO, K

 ------------------ HEAT EXCHANGE IN THE CYLINDER --------------------
 1302.9     - T_eq     - Average Equivalent Temperature of Cycle, K
 669.50     - hc_c     - Aver. Factor of Heat Transfer in Cyl., W/m2/K
 800.00     - Tw_pist  - Average Piston Crown Temperature, K
 440.00     - Tw_liner - Average Cylinder Liner Temperature, K
```

```
 700.00     - Tw_head  - Average Head Wall Temperature, K
 392.10     - Tw_cool  - Average Temperature of Cooled Surface
                head     of Cylinder Head, K
 398.16     - Tboil    - Boiling Temp. in Liquid Cooling System, K
 12519.     - hc_cool  - Average Factor of Heat Transfer, W/(m2*K)
                         from head cooled surface to coolant
 1643.4     - q_head   - Heat Flow in a Cylinder Head, J/s
 1370.8     - q_pist   - Heat Flow in a Piston Crown, J/s
 1145.7     - q_liner  - Heat Flow in a Cylinder Liner, J/s

 --------------- MAIN ENGINE CONSTRUCTION PARAMETERS -----------------
 15.500     - CR       - Compression Ratio
 4.5897     - CR_opn.h - CR in view of losses due to open height of porting
 8.0000     - n_inj    - Number of Injector Nozzles
0.13100     - d_inj    - Injector Nozzles Bore, mm
 7.5000     - Phi_inj  - Injection Duration for spec. Inject. Profile, deg.
 0.0000     - m_f_ip   - Fuel Mass for specified Injection Profile, g
-112.00     - IVO      - Intake Valve Opening, deg. before DC
 127.00     - IVC      - Intake Valve Closing, deg. after BDC
 68.000     - EVO      - Exhaust Valve Opening, deg. before BDC
 112.00     - EVC      - Exhaust Valve Closing, deg. after  DC

 ----------------- COMPRESSOR PARAMETERS  LP stage -------------------
 15000.     - RPM_C.lp - Rotor Speed of LPC, rev/min
 3.7787     - P_C.lp   - Power of LP Compressor, kW
0.70000     - Eta_C.lp - Adiabatic Efficiency of LP Compressor
0.02814     - m_C.lp   - Mass Airflow of LP Compressor, kg/sec
0.49062     - m*_C.lp  - Mass Airflow Parameter, kg SQRT(K)/(s bar)
0.02842     - m.cor_Clp- Corrected Mass Airflow of LPC, kg/s
 868.93     - RPM*_C.lp- Rotor Speed Parameter, rev/min SQRT(K)
 15000.     - RPMcor_lp- Corrected Rotor Speed, rev/min
 2.6000     - PR_C.lp  - Pressure Ratio of LP Compressor
 0.0000     - Kpi_C.lp - Factor Kpi of LP Compressor
0.99000     - po_iC.lp - Inlet Total Pressure of LPC, bar
 298.00     - To_iC.lp - Inlet Total Temperature of LPC, K
 2.5740     - po_"C.lp - Total Discharge Press.(before LP cooler), bar
 431.63     - To_"C.lp - Total Discharge Temp. (before LP cooler), K
0.90000     - Ecool.lp - Thermal Efficiency of LP Air Inter-cooler
 298.00     - Tcool.lp - LP Inter-cooler Refrigerant Temperature, K
 2.5540     - po_C.lp  - Total Pressure after LP Inter-cooler, bar
 311.36     - To_C.lp  - Total Temperature after LP Inter-cooler, K

 ----------------- COMPRESSOR PARAMETERS  HP stage -------------------
 15000.     - RPM_C.hp - Rotor Speed of HPC, rev/min
 5.3028     - P_C.hp   - Power of HPC, kW
0.85000     - Eta_C.hp - Adiabatic Efficiency of HPC
0.02814     - m_C.hp   - Mass Airflow of HP Compressor, kg/s
0.19439     - m*_C.hp  - Mass Airflow Parameter, kg SQRT(K)/(s bar)
0.01126     - m.cor_Chp- Corrected Mass Airflow of HPC, kg/s
 850.08     - RPM*_C.hp- Rotor Speed Parameter, rev/min SQRT(K)
 14675.     - RPMcor_hp- Corrected Rotor Speed, rev/min
 4.2500     - PR_C.hp  - Pressure Ratio of HP Compressor
 0.0000     - Kpi_C.hp - Factor Kpi of HP Compressor
 2.5540     - po_iC.hp - Inlet Total Pressure of HPC, bar
 311.36     - To_iC.hp - Inlet Total Temperature of HPC, K
 10.854     - po_"C.hp - Total Discharge Press. (before HP cooler), bar
 498.89     - To_"C.hp - Total Discharge Temp. (before HP cooler), K
0.90000     - Ecool.hp - Thermal Efficiency of HP Air Inter-cooler
 298.00     - Tcool.hp - HP Inter-cooler Refrigerant Temperature, K
 10.834     - po_C.hp  - Total Pressure after Inter-cooler, bar
 318.09     - To_C.hp  - Total Temperature after Inter-cooler, K

 ----------------- TURBINE PARAMETERS  HP stage ----------------------
 15000.     - RPM_T.hp - HP Turbine Rotor Speed, rev/min
```

```
  0.0000      - P_T.hp   - Effective Power of HPT, kW
  1.0000      - Eta_T.hp - Internal turbine Efficiency of HPT
 0.90900      - Eta_mT.hp- Mechanical Efficiency of HPT
 0.03000      - m_T.hp   - Mass Gasflow of HPT, kg/s
 0.29102      - m*_T.hp  - Mass Gasflow Parameter, kg SQRT(K)/s kPa
  540.28      - RPM*_T.hp- Rotor Speed Parameter, rev/min SQRT(K)
  1.0000      - PR_T.hp  - Expansion Pressure Ratio of HPT
  0.0000      - B_T.hp   - Relative Work B=118.34 {1-PR**[(1-k)/k]} Eta_T
  2.8618      - po_T.hp  - Inlet Total Pressure of HPT, bar
  770.81      - To_T.hp  - Inlet Total Temperature of HPT, K
  2.8618      - po_eT.hp - HP Turbine Exhaust Back Pressure, bar
  770.81      - To_eT.hp - HP Turbine Exhaust Back Temperature, K

  ----------------- TURBINE PARAMETERS  LP stage -----------------------
  15000.      - RPM_T.lp - LP Turbine Rotor Speed, rev/min
  3.7866      - P_T.lp   - Effective Power of LPT, kW
 0.70721      - Eta_T.lp - Adiabatic Efficiency of LPT
 0.90900      - Eta_mT.lp- Mechanical Efficiency  of LPT
 0.03000      - m_T.lp   - Mass Gasflow of LPT, kg/s
 0.29102      - m*_T.lp  - Mass Gasflow Parameter, kg SQRT(K)/s kPa
  540.28      - RPM*_T.lp- Rotor Speed Parameter, rev/min SQRT(K)
  2.8036      - PR_T.lp  - Expansion Pressure Ratio of LPT
  18.888      - B_T.lp   - Relative Work B=118.34 {1-PR**[(1-k)/k]} Eta_T
  2.8618      - po_T.lp  - Inlet Total Pressure of LPT, bar
  770.81      - To_T.lp  - Inlet Total Temperature of LPT, K
  1.0208      - po_eT.lp - LP Turbine Exhaust Back Pressure, bar
  643.26      - To_eT.lp - LP 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 ¦ 54.0 ¦pist. bowl¦ 77.54    2.22   20.14   13.55    0.10   0.00
-------------------------------------------------------------------------
Sum of all sprays     % 100.¦ 59.45    5.42    9.38   25.74    0.01   0.00
=========================================================================
Evaporation constants  bi   ¦ 44544    6284   37111   31359   29235    224
=========================================================================
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: 6.00
   Ratio¦  Rs of piston bowl     4.35 ¦   Rs  ¦-by Razleytsev    : 3.82

____________________
Versions:     Kernel 20.03.10;  RK-model 03.03.10;  NOx-model 02.04.10
```







Injection and HRR

Table 6

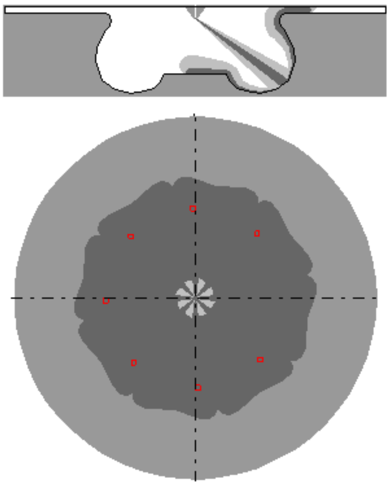
Z-engine simulation data at: BMEP=6.3 @ 1500 RPM (Case #4)

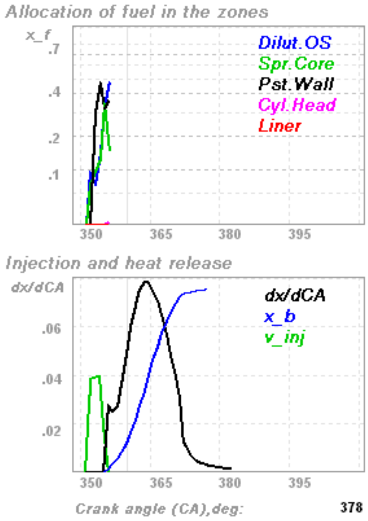
```
2010-05-03 11-07-51 Z-engine
 Mode: #6  : RPM=1500, BMEP=6.3;
 Title:
 www.diesel-rk.bmstu.ru
  Fuel:      Diesel No. 2

   ---- PARAMETERS OF ENGINE WITH TURBOCOMPAUNDING OR SUPERCHARGING ----
   8.9680     - P_ovrl   - Overall Power in view of geared T/C/TC, kW
  -2.8750     - dP_add   - Power added by geared Turb/Comp/TC, kW
   57.096     - Torq_ovrl- Overall Torque in view of geared T/C/TC, N m
   6.2932     - BMEP_ovrl- Overall BMEP, bar
  0.26093     - SFC_ovrl - Overall Specific Fuel Consumption, kg/kWh
  0.32463     - Eta_ovrl - Overall Engine Efficiency
   10.000     - R_gear   - Gear ratio of TK speed reducer
  0.95000     - Eta_mC.hp- Mechanical Efficiency of HPC
  -2.8737     - dPdrv_hp - Power added by geared Unit of HP stage, kW
   10.000     - R_gear.lp- Gear Ratio of LP Units and drive shaft coupling
  0.95000     - Eta_mC.lp- Mechanical Efficiency of LP Compressor
 -0.00135     - dPdrv_lp - Power added by geared Unit of LP stage, kW

   ----------------- PARAMETERS OF EFFICIENCY AND POWER ----------------
   1500.0     - RPM      - Engine Speed, rev/min
   11.843     - P_eng    - Piston Engine Power, kW
   8.3108     - BMEP     - Brake Mean Effective Pressure, bar
   75.401     - Torque   - Brake Torque, N m
  0.01300     - m_f      - Mass of Fuel Supplied per cycle, g
  0.19758     - SFC      - Specific Fuel Consumption, kg/kWh
  0.42871     - Eta_f    - Efficiency of piston engine
   9.2482     - IMEP     - Indicated Mean Effective Pressure, bar
  0.47706     - Eta_i    - Indicated Efficiency
  0.93740     - FMEP     - Friction Mean Effective Pressure, bar (Intern.Exp)
  0.89864     - Eta_m    - Mechanical Efficiency of Piston Engine

   --------------------- ENVIRONMENTAL PARAMETERS ----------------------
   1.0000     - p_sea    - Static Atmospheric Pressure on sea level, bar
   298.00     - T_sea    - Static Atmospheric Temperature on sea level, K
   0.0000     - A_ab.sea - Altitude Above Sea Level, km
   0.0000     - v_flight - Velosity of Flight, km/h (for aircraft engine)
   1.0000     - p_amb    - Static Ambient Pressure, bar
   298.00     - T_amb    - Static Ambient Temperature, K
   1.0000     - po_amb   - Total Ambient Pressure, bar
   298.00     - To_amb   - Total Ambient Temperature, K
   1.0100     - p_Te     - Exhaust Back Pressure, bar (after turbine)
  0.99500     - po_afltr - Total Pressure after Induction Air Filter, bar

   ------------------ TURBOCHARGING AND GAS EXCHANGE -------------------
   5.8152     - p_C      - Pressure before Inlet Manifold, bar
   317.98     - T_C      - Temperature before Inlet Manifold, K
  0.01398     - m_air    - Total Mass Airflow (+EGR) of Piston Engine, kg/s
  0.66621     - Eta_TC   - Turbocharger Efficiency
   1.6274     - po_T     - Average Total Turbine Inlet Pressure, bar
   748.39     - To_T     - Average Total Turbine Inlet Temperature, K
  0.01488     - m_gas    - Mass Exhaust Gasflow of Pison Engine, g/s
   1.4843     - A/F_eq.t - Total Air Fuel Equivalence Ratio (Lambda)
  0.67371     - F/A_eq.t - Total Fuel Air Equivalence Ratio
  0.17877     - Eta_v    - Volumetric Efficiency
  0.30201     - x_r      - Residual Gas Mass Fraction
  0.86175     - Phi      - Coeff. of Scavenging (Delivery Ratio / Eta_v)
   0.0000     - BF_int   - Burnt Gas Fraction Backflowed into the Intake, %
   1.5085     - %Blow-by - % of Blow-by through piston rings
```

```
 ---------------------------- INTAKE SYSTEM ---------------------------
 5.8086     - p_int    - Average Intake Manifold Pressure, bar
 316.30     - T_int    - Average Intake Manifold Temperature, K
 1.1115     - v_int    - Average Gas Velocity in intake manifold, m/s
 316.25     - Tw_int   - Average Intake Manifold Wall Temperature, K
 135.75     - hc_int   - Heat Transfer Coeff. in Intake Manifold, W/(m2*K)
 60.000     - hc_int.p - Heat Transfer Coeff. in Intake Port, W/(m2*K)

 --------------------------- EXHAUST SYSTEM ---------------------------
 1.6082     - p_exh    - Average Exhaust Manifold Gas Pressure, bar
 730.64     - T_exh    - Average Exhaust Manifold Gas Temperature, K
 9.9791     - v_exh    - Average Gas Velocity in exhaust manifold, m/s
 96.019     - Sh       - Strouhal number: Sh=a*Tau/L (has to be: Sh > 8)
 581.48     - Tw_exh   - Average Exhaust Manifold Wall Temperature, K
 90.000     - hc_exh   - Heat Transfer Coeff. in Exhaust Manifold, W/(m2*K)
 127.01     - hc_exh.p - Heat Transfer Coeff. in Exhaust Port, W/(m2*K)

 ---------------------------- COMBUSTION ----------------------------
 1.7654     - A/F_eq   - Air Fiel Equival. Ratio (Lambda) in the Cylinder
0.56645     - F/A_eq   - Fuel Air Equivalence Ratio in the Cylinder
 94.996     - p_max    - Maximum Cylinder Pressure, bar
 1922.9     - T_max    - Maximum Cylinder Temperature, K
 12.000     - CA_p.max - Angle of Max. Cylinder Pressure, deg. A.TDC
 15.000     - CA_t.max - Angle of Max. Cylinder Temperature, deg. A.TDC
 4.6642     - dp/dTheta- Max. Rate of Pressure Rise, bar/deg.
 1.4715     - Ring_Intn- Ringing / Knock Intensity, MW/m2
Injection: Injector
 1171.5     - p_inj.max- Max. Injection Pres. (before nozzles), bar
 10.723     - d_32     - Sauter Mean Diameter of Drops, microns
 9.0000     - SOI      - Start Of Injection or Ignition Timing, deg. B.TDC
 4.2000     - Phi_inj  - Duration of Injection, CA deg.
 8.0711     - Phi_ign  - Ignition Delay Period, deg.
            -   ...    - Integral  calc. by CHEMKIN for Dies. Oil:   8.1
0.92886     - SOC      - Start of Combustion, deg. B.TDC
0.99000     - x_e.id   - Fuel Mass Fraction Evaporated during Ignit. Delay
 42.600     - Phi_z    - Combustion duration, deg.
 4.2177     - Rs_tdc   - Swirl Ratio in the Combustion Chamber at TDC
 1.6000     - Rs_ivc   - Swirl Ratio in the Cylinder at IVC
 12.384     - W_swirl  - Max. Air Swirl Velocity, m/s  at cylinder R=   19

 ------------------------- ECOLOGICAL PARAMETERS ----------------------
 8.1822     - Hartridge- Hartridge Smoke Level
0.89805     - Bosch    - Bosch Smoke Number
0.19956     - K.m-1    - Factor of Absolute Light Absorption, 1/m
0.17965     - PM       - Specific Particulate Matter, g/kWh
 840.76     - CO2      - Specific Carbon dioxide emission, g/kWh
 176.63     - NOx.dry  - Fraction of dry NOx in exh. gas, ppm
0.73722     - NO       - Specif. NOx emiss. reduc. to NO, g/kWh(DKM)
0.70415     - SE       - Summary emission of PM and NOx
 0.0000     - SO2      - Specific SO2 emission, g/kWh

 ------------------------- CYLINDER PARAMETERS -----------------------
 7.6825     - p_ivc    - Pressure at IVC, bar
 586.65     - T_ivc    - Temperature at IVC, K
 59.353     - p_tdc    - Compression Pressure (at TDC), bar
 991.23     - T_tdc    - Compression Temperature (at TDC), K
 4.8866     - p_evo    - Pressure at EVO, bar
 942.22     - T_evo    - Temperaure at EVO, K

 ------------------- HEAT EXCHANGE IN THE CYLINDER --------------------
 1293.2     - T_eq     - Average Equivalent Temperature of Cycle, K
 390.23     - hc_c     - Aver. Factor of Heat Transfer in Cyl., W/m2/K
 800.00     - Tw_pist  - Average Piston Crown Temperature, K
```

```
 440.00     - Tw_liner - Average Cylinder Liner Temperature, K
 700.00     - Tw_head  - Average Head Wall Temperature, K
 380.53     - Tw_cool  - Average Temperature of Cooled Surface
                 head    of Cylinder Head, K
 398.16     - Tboil    - Boiling Temp. in Liquid Cooling System, K
 10788.     - hc_cool  - Average Factor of Heat Transfer, W/(m2*K)
                         from head cooled surface to coolant
 942.39     - q_head   - Heat Flow in a Cylinder Head, J/s
 783.52     - q_pist   - Heat Flow in a Piston Crown, J/s
 656.74     - q_liner  - Heat Flow in a Cylinder Liner, J/s

 --------------- MAIN ENGINE CONSTRUCTION PARAMETERS -----------------
 15.500     - CR       - Compression Ratio
 4.5897     - CR_opn.h - CR in view of losses due to open height of porting
 8.0000     - n_inj    - Number of Injector Nozzles
0.13100     - d_inj    - Injector Nozzles Bore, mm
 4.2000     - Phi_inj  - Injection Duration for spec. Inject. Profile, deg.
 0.0000     - m_f_ip   - Fuel Mass for specified Injection Profile, g
-112.00     - IVO      - Intake Valve Opening, deg. before DC
 127.00     - IVC      - Intake Valve Closing, deg. after BDC
 68.000     - EVO      - Exhaust Valve Opening, deg. before BDC
 112.00     - EVC      - Exhaust Valve Closing, deg. after  DC

 ----------------- COMPRESSOR PARAMETERS  LP stage --------------------
 15000.     - RPM_C.lp - Rotor Speed of LPC, rev/min
0.78254     - P_C.lp   - Power of LP Compressor, kW
0.54000     - Eta_C.lp - Adiabatic Efficiency of LP Compressor
0.01398     - m_C.lp   - Mass Airflow of LP Compressor, kg/sec
0.24260     - m*_C.lp  - Mass Airflow Parameter, kg SQRT(K)/(s bar)
0.01405     - m.cor_Clp- Corrected Mass Airflow of LPC, kg/s
 868.93     - RPM*_C.lp- Rotor Speed Parameter, rev/min SQRT(K)
 15000.     - RPMcor_lp- Corrected Rotor Speed, rev/min
 1.4000     - PR_C.lp  - Pressure Ratio of LP Compressor
 0.0000     - Kpi_C.lp - Factor Kpi of LP Compressor
0.99500     - po_iC.lp - Inlet Total Pressure of LPC, bar
 298.00     - To_iC.lp - Inlet Total Temperature of LPC, K
 1.3930     - po_"C.lp - Total Discharge Press.(before LP cooler), bar
 353.69     - To_"C.lp - Total Discharge Temp. (before LP cooler), K
0.90000     - Ecool.lp - Thermal Efficiency of LP Air Inter-cooler
 298.00     - Tcool.lp - LP Inter-cooler Refrigerant Temperature, K
 1.3730     - po_C.lp  - Total Pressure after LP Inter-cooler, bar
 303.57     - To_C.lp  - Total Temperature after LP Inter-cooler, K

 ----------------- COMPRESSOR PARAMETERS  HP stage -------------------
 15000.     - RPM_C.hp - Rotor Speed of HPC, rev/min
 2.7300     - P_C.hp   - Power of HPC, kW
0.80000     - Eta_C.hp - Adiabatic Efficiency of HPC
0.01398     - m_C.hp   - Mass Airflow of HP Compressor, kg/s
0.17744     - m*_C.hp  - Mass Airflow Parameter, kg SQRT(K)/(s bar)
0.01028     - m.cor_Chp- Corrected Mass Airflow of HPC, kg/s
 860.92     - RPM*_C.hp- Rotor Speed Parameter, rev/min SQRT(K)
 14862.     - RPMcor_hp- Corrected Rotor Speed, rev/min
 4.2500     - PR_C.hp  - Pressure Ratio of HP Compressor
 0.0000     - Kpi_C.hp - Factor Kpi of HP Compressor
 1.3730     - po_iC.hp - Inlet Total Pressure of HPC, bar
 303.57     - To_iC.hp - Inlet Total Temperature of HPC, K
 5.8352     - po_"C.hp - Total Discharge Press. (before HP cooler), bar
 497.83     - To_"C.hp - Total Discharge Temp. (before HP cooler), K
0.90000     - Ecool.hp - Thermal Efficiency of HP Air Inter-cooler
 298.00     - Tcool.hp - HP Inter-cooler Refrigerant Temperature, K
 5.8152     - po_C.hp  - Total Pressure after Inter-cooler, bar
 317.98     - To_C.hp  - Total Temperature after Inter-cooler, K

 ----------------- TURBINE PARAMETERS  HP stage ----------------------
```

```
   15000.      - RPM_T.hp - HP Turbine Rotor Speed, rev/min
   0.0000      - P_T.hp   - Effective Power of HPT, kW
   1.0000      - Eta_T.hp - Internal turbine Efficiency of HPT
  0.90900      - Eta_mT.hp- Mechanical Efficiency of HPT
  0.01488      - m_T.hp   - Mass Gasflow of HPT, kg/s
  0.25006      - m*_T.hp  - Mass Gasflow Parameter, kg SQRT(K)/s kPa
   548.31      - RPM*_T.hp- Rotor Speed Parameter, rev/min SQRT(K)
   1.0000      - PR_T.hp  - Expansion Pressure Ratio of HPT
   0.0000      - B_T.hp   - Relative Work B=118.34 {1-PR**[(1-k)/k]} Eta_T
   1.6274      - po_T.hp  - Inlet Total Pressure of HPT, bar
   748.39      - To_T.hp  - Inlet Total Temperature of HPT, K
   1.6274      - po_eT.hp - HP Turbine Exhaust Back Pressure, bar
   748.39      - To_eT.hp - HP Turbine Exhaust Back Temperature, K

 ----------------- TURBINE PARAMETERS  LP stage ----------------------
   15000.      - RPM_T.lp - LP Turbine Rotor Speed, rev/min
  0.78126      - P_T.lp   - Effective Power of LPT, kW
  0.61117      - Eta_T.lp - Adiabatic Efficiency of LPT
  0.90900      - Eta_mT.lp- Mechanical Efficiency  of LPT
  0.01488      - m_T.lp   - Mass Gasflow of LPT, kg/s
  0.25006      - m*_T.lp  - Mass Gasflow Parameter, kg SQRT(K)/s kPa
   548.31      - RPM*_T.lp- Rotor Speed Parameter, rev/min SQRT(K)
   1.6134      - PR_T.lp  - Expansion Pressure Ratio of LPT
   8.0944      - B_T.lp   - Relative Work B=118.34 {1-PR**[(1-k)/k]} Eta_T
   1.6274      - po_T.lp  - Inlet Total Pressure of LPT, bar
   748.39      - To_T.lp  - Inlet Total Temperature of LPT, K
   1.0087      - po_eT.lp - LP Turbine Exhaust Back Pressure, bar
   696.03      - To_eT.lp - LP 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 ¦ 54.0 ¦pist. bowl¦ 60.18   7.40   32.40   26.09    0.01   0.00
------------------------------------------------------------------------
Sum of all sprays    % 100.¦ 36.12  23.95   10.77   29.16    0.00   0.00
========================================================================
Evaporation constants  bi  ¦****** 639315  ******  ******  ******  19634
========================================================================
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:10.71
   Ratio¦  Rs of piston bowl     4.22 ¦   Rs  ¦-by Razleytsev    : 4.31
____________________
Versions:     Kernel 20.03.10;  RK-model 03.03.10;  NOx-model 02.04.10
```





Injection and HRR

Table 7

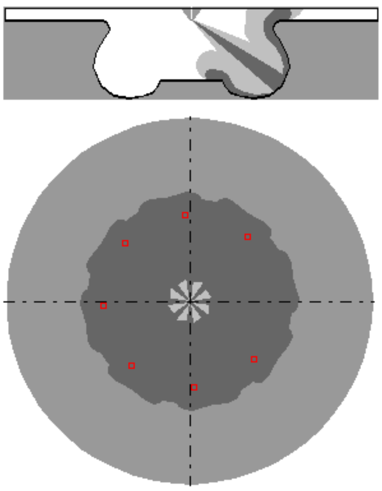
Z-engine simulation data at: BMEP=24 @ 3600 RPM (Case #5)

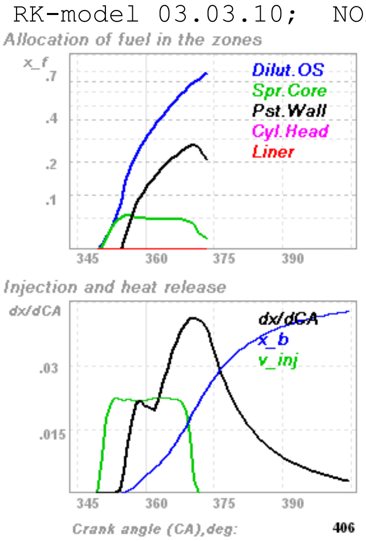
```
2010-05-14 16-14-17 Z-engine
 Mode: #2 :: Full load IntakeDur=22 Single inj;
 Title: Intake dur=21 Theta=10.6
 www.diesel-rk.bmstu.ru
  Fuel:      Diesel No. 2

   ---- PARAMETERS OF ENGINE WITH TURBOCOMPAUNDING OR SUPERCHARGING ----
   59.501      - P_ovrl   - Overall Power in view of geared T/C/TC, kW
  -16.810      - dP_add   - Power added by geared Turb/Comp/TC, kW
   157.84      - Torq_ovrl- Overall Torque in view of geared T/C/TC, N m
   17.398      - BMEP_ovrl- Overall BMEP, bar
  0.24685      - SFC_ovrl - Overall Specific Fuel Consumption, kg/kWh
  0.34314      - Eta_ovrl - Overall Engine Efficiency
   10.000      - R_gear   - Gear ratio of TK speed reducer
  0.95000      - Eta_mC.hp- Mechanical Efficiency of HPC
  -16.772      - dPdrv_hp - Power added by geared Unit of HP stage, kW
   10.000      - R_gear.lp- Gear Ratio of LP Units and drive shaft coupling
  0.95000      - Eta_mC.lp- Mechanical Efficiency of LP Compressor
 -0.03787      - dPdrv_lp - Power added by geared Unit of LP stage, kW

   ----------------- PARAMETERS OF EFFICIENCY AND POWER ----------------
   3600.0      - RPM      - Engine Speed, rev/min
   76.311      - P_eng    - Piston Engine Power, kW
   22.313      - BMEP     - Brake Mean Effective Pressure, bar
   202.44      - Torque   - Brake Torque, N m
  0.03400      - m_f      - Mass of Fuel Supplied per cycle, g
  0.19248      - SFC      - Specific Fuel Consumption, kg/kWh
  0.44009      - Eta_f    - Efficiency of piston engine
   24.740      - IMEP     - Indicated Mean Effective Pressure, bar
  0.48796      - Eta_i    - Indicated Efficiency
   2.4270      - FMEP     - Friction Mean Effective Pressure, bar (Intern.Exp)
  0.90190      - Eta_m    - Mechanical Efficiency of Piston Engine

   --------------------- ENVIRONMENTAL PARAMETERS ----------------------
   1.0000      - p_sea    - Static Atmospheric Pressure on sea level, bar
   298.00      - T_sea    - Static Atmospheric Temperature on sea level, K
   0.0000      - A_ab.sea - Altitude Above Sea Level, km
   0.0000      - v_flight - Velosity of Flight, km/h (for aircraft engine)
   1.0000      - p_amb    - Static Ambient Pressure, bar
   298.00      - T_amb    - Static Ambient Temperature, K
   1.0000      - po_amb   - Total Ambient Pressure, bar
   298.00      - 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 -------------------
   17.805      - p_C      - Pressure before Inlet Manifold, bar
   319.38      - T_C      - Temperature before Inlet Manifold, K
  0.08242      - m_air    - Total Mass Airflow (+EGR) of Piston Engine, kg/s
  0.74012      - Eta_TC   - Turbocharger Efficiency
   4.2477      - po_T     - Average Total Turbine Inlet Pressure, bar
   910.76      - To_T     - Average Total Turbine Inlet Temperature, K
  0.08935      - m_gas    - Mass Exhaust Gasflow of Pison Engine, g/s
   1.3938      - A/F_eq.t - Total Air Fuel Equivalence Ratio (Lambda)
  0.71747      - F/A_eq.t - Total Fuel Air Equivalence Ratio
  0.14248      - Eta_v    - Volumetric Efficiency
  0.30604      - x_r      - Residual Gas Mass Fraction
  0.87103      - Phi      - Coeff. of Scavenging (Delivery Ratio / Eta_v)
   0.0000      - BF_int   - Burnt Gas Fraction Backflowed into the Intake, %
  0.64221      - %Blow-by - % of Blow-by through piston rings
```

```
 --------------------------- INTAKE SYSTEM ---------------------------
 17.771     - p_int    - Average Intake Manifold Pressure, bar
 322.18     - T_int    - Average Intake Manifold Temperature, K
 2.1803     - v_int    - Average Gas Velocity in intake manifold, m/s
 325.17     - Tw_int   - Average Intake Manifold Wall Temperature, K
 188.06     - hc_int   - Heat Transfer Coeff. in Intake Manifold, W/(m2*K)
 164.41     - hc_int.p - Heat Transfer Coeff. in Intake Port, W/(m2*K)

 -------------------------- EXHAUST SYSTEM ---------------------------
 4.0080     - p_exh    - Average Exhaust Manifold Gas Pressure, bar
 896.23     - T_exh    - Average Exhaust Manifold Gas Temperature, K
 29.925     - v_exh    - Average Gas Velocity in exhaust manifold, m/s
 44.310     - Sh       - Strouhal number: Sh=a*Tau/L (has to be: Sh > 8)
 745.63     - Tw_exh   - Average Exhaust Manifold Wall Temperature, K
 159.39     - hc_exh   - Heat Transfer Coeff. in Exhaust Manifold, W/(m2*K)
 231.75     - hc_exh.p - Heat Transfer Coeff. in Exhaust Port, W/(m2*K)

 ---------------------------- COMBUSTION ----------------------------
 1.6468     - A/F_eq   - Air Fiel Equival. Ratio (Lambda) in the Cylinder
0.60722     - F/A_eq   - Fuel Air Equivalence Ratio in the Cylinder
 198.54     - p_max    - Maximum Cylinder Pressure, bar
 1747.6     - T_max    - Maximum Cylinder Temperature, K
 11.000     - CA_p.max - Angle of Max. Cylinder Pressure, deg. A.TDC
 23.000     - CA_t.max - Angle of Max. Cylinder Temperature, deg. A.TDC
 5.3690     - dp/dTheta- Max. Rate of Pressure Rise, bar/deg.
 5.1229     - Ring_Intn- Ringing / Knock Intensity, MW/m2
Injection: Common Rail
 1488.5     - p_inj.max- Max. Injection Pres. (before nozzles), bar
 7.6189     - d_32     - Sauter Mean Diameter of Drops, microns
 10.600     - SOI      - Start Of Injection or Ignition Timing, deg. B.TDC
 22.000     - Phi_inj  - Duration of Injection, CA deg.
 4.5548     - Phi_ign  - Ignition Delay Period, deg.
            -   ...    - Integral  calc. by CHEMKIN for Dies. Oil:   4.6
 6.0452     - SOC      - Start of Combustion, deg. B.TDC
0.08571     - x_e.id   - Fuel Mass Fraction Evaporated during Ignit. Delay
 93.200     - Phi_z    - Combustion duration, deg.
 2.6803     - Rs_tdc   - Swirl Ratio in the Combustion Chamber at TDC
 1.0981     - Rs_ivc   - Swirl Ratio in the Cylinder at IVC
 18.888     - W_swirl  - Max. Air Swirl Velocity, m/s  at cylinder R=   19

 ------------------------ ECOLOGICAL PARAMETERS ----------------------
 9.1684     - Hartridge- Hartridge Smoke Level
 1.0018     - Bosch    - Bosch Smoke Number
0.22483     - K.m-1    - Factor of Absolute Light Absorption, 1/m
0.18682     - PM       - Specific Particulate Matter, g/kWh
 795.42     - CO2      - Specific Carbon dioxide emission, g/kWh
 107.33     - NOx.dry  - Fraction of dry NOx in exh. gas, ppm
0.39308     - NO       - Specif. NOx emiss. reduc. to NO, g/kWh(DKM)
0.67890     - SE       - Summary emission of PM and NOx
 0.0000     - SO2      - Specific SO2 emission, g/kWh

 ------------------------- CYLINDER PARAMETERS -----------------------
 27.479     - p_ivc    - Pressure at IVC, bar
 696.62     - T_ivc    - Temperature at IVC, K
 161.62     - p_tdc    - Compression Pressure (at TDC), bar
 1084.5     - T_tdc    - Compression Temperature (at TDC), K
 14.748     - p_evo    - Pressure at EVO, bar
 1136.3     - T_evo    - Temperaure at EVO, K

 ------------------ HEAT EXCHANGE IN THE CYLINDER --------------------
 1229.7     - T_eq     - Average Equivalent Temperature of Cycle, K
 1285.2     - hc_c     - Aver. Factor of Heat Transfer in Cyl., W/m2/K
 800.00     - Tw_pist  - Average Piston Crown Temperature, K
```

```
   440.00     - Tw_liner - Average Cylinder Liner Temperature, K
   700.00     - Tw_head  - Average Head Wall Temperature, K
   409.78     - Tw_cool  - Average Temperature of Cooled Surface
                   head    of Cylinder Head, K
   398.16     - Tboil    - Boiling Temp. in Liquid Cooling System, K
   13684.     - hc_cool  - Average Factor of Heat Transfer, W/(m2*K)
                           from head cooled surface to coolant
   2771.5     - q_head   - Heat Flow in a Cylinder Head, J/s
   2248.3     - q_pist   - Heat Flow in a Piston Crown, J/s
   3313.0     - q_liner  - Heat Flow in a Cylinder Liner, J/s

   --------------- MAIN ENGINE CONSTRUCTION PARAMETERS -----------------
   15.500     - CR       - Compression Ratio
   3.7840     - CR_opn.h - CR in view of losses due to open height of porting
   8.0000     - n_inj    - Number of Injector Nozzles
  0.13100     - 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
  -112.00     - IVO      - Intake Valve Opening, deg. before DC
   134.00     - IVC      - Intake Valve Closing, deg. after BDC
   68.000     - EVO      - Exhaust Valve Opening, deg. before BDC
   112.00     - EVC      - Exhaust Valve Closing, deg. after  DC

   ----------------- COMPRESSOR PARAMETERS  LP stage -------------------
   36000.     - RPM_C.lp - Rotor Speed of LPC, rev/min
   17.724     - P_C.lp   - Power of LP Compressor, kW
  0.72000     - Eta_C.lp - Adiabatic Efficiency of LP Compressor
  0.08242     - m_C.lp   - Mass Airflow of LP Compressor, kg/sec
   1.4518     - m*_C.lp  - Mass Airflow Parameter, kg SQRT(K)/(s bar)
  0.08410     - m.cor_Clp- Corrected Mass Airflow of LPC, kg/s
   2085.4     - RPM*_C.lp- Rotor Speed Parameter, rev/min SQRT(K)
   36000.     - RPMcor_lp- Corrected Rotor Speed, rev/min
   4.3000     - PR_C.lp  - Pressure Ratio of LP Compressor
   0.0000     - Kpi_C.lp - Factor Kpi of LP Compressor
  0.98000     - po_iC.lp - Inlet Total Pressure of LPC, bar
   298.00     - To_iC.lp - Inlet Total Temperature of LPC, K
   4.2140     - po_"C.lp - Total Discharge Press.(before LP cooler), bar
   511.98     - To_"C.lp - Total Discharge Temp. (before LP cooler), K
  0.90000     - Ecool.lp - Thermal Efficiency of LP Air Inter-cooler
   298.00     - Tcool.lp - LP Inter-cooler Refrigerant Temperature, K
   4.1940     - po_C.lp  - Total Pressure after LP Inter-cooler, bar
   319.40     - To_C.lp  - Total Temperature after LP Inter-cooler, K

   ----------------- COMPRESSOR PARAMETERS  HP stage -------------------
   36000.     - RPM_C.hp - Rotor Speed of HPC, rev/min
   15.934     - P_C.hp   - Power of HPC, kW
  0.85000     - Eta_C.hp - Adiabatic Efficiency of HPC
  0.08242     - m_C.hp   - Mass Airflow of HP Compressor, kg/s
  0.35120     - m*_C.hp  - Mass Airflow Parameter, kg SQRT(K)/(s bar)
  0.02034     - m.cor_Chp- Corrected Mass Airflow of HPC, kg/s
   2014.4     - RPM*_C.hp- Rotor Speed Parameter, rev/min SQRT(K)
   34773.     - RPMcor_hp- Corrected Rotor Speed, rev/min
   4.2500     - PR_C.hp  - Pressure Ratio of HP Compressor
   0.0000     - Kpi_C.hp - Factor Kpi of HP Compressor
   4.1940     - po_iC.hp - Inlet Total Pressure of HPC, bar
   319.40     - To_iC.hp - Inlet Total Temperature of HPC, K
   17.825     - po_"C.hp - Total Discharge Press. (before HP cooler), bar
   511.77     - To_"C.hp - Total Discharge Temp. (before HP cooler), K
  0.90000     - Ecool.hp - Thermal Efficiency of HP Air Inter-cooler
   298.00     - Tcool.hp - HP Inter-cooler Refrigerant Temperature, K
   17.805     - po_C.hp  - Total Pressure after Inter-cooler, bar
   319.38     - To_C.hp  - Total Temperature after Inter-cooler, K
```

```
 ----------------- TURBINE PARAMETERS  HP stage ----------------------
 36000.     - RPM_T.hp - HP Turbine Rotor Speed, rev/min
 0.0000     - P_T.hp   - Effective Power of HPT, kW
 1.0000     - Eta_T.hp - Internal turbine Efficiency of HPT
0.90900     - Eta_mT.hp- Mechanical Efficiency of HPT
0.08935     - m_T.hp   - Mass Gasflow of HPT, kg/s
0.63480     - m*_T.hp  - Mass Gasflow Parameter, kg SQRT(K)/s kPa
 1192.9     - RPM*_T.hp- Rotor Speed Parameter, rev/min SQRT(K)
 1.0000     - PR_T.hp  - Expansion Pressure Ratio of HPT
 0.0000     - B_T.hp   - Relative Work B=118.34 {1-PR**[(1-k)/k]} Eta_T
 4.2477     - po_T.hp  - Inlet Total Pressure of HPT, bar
 910.76     - To_T.hp  - Inlet Total Temperature of HPT, K
 4.2477     - po_eT.hp - HP Turbine Exhaust Back Pressure, bar
 910.76     - To_eT.hp - HP Turbine Exhaust Back Temperature, K

 ----------------- TURBINE PARAMETERS  LP stage ----------------------
 36000.     - RPM_T.lp - LP Turbine Rotor Speed, rev/min
 17.688     - P_T.lp   - Effective Power of LPT, kW
0.71813     - Eta_T.lp - Adiabatic Efficiency of LPT
0.90900     - Eta_mT.lp- Mechanical Efficiency  of LPT
0.08935     - m_T.lp   - Mass Gasflow of LPT, kg/s
0.63480     - m*_T.lp  - Mass Gasflow Parameter, kg SQRT(K)/s kPa
 1192.9     - RPM*_T.lp- Rotor Speed Parameter, rev/min SQRT(K)
 4.0915     - PR_T.lp  - Expansion Pressure Ratio of LPT
 25.071     - B_T.lp   - Relative Work B=118.34 {1-PR**[(1-k)/k]} Eta_T
 4.2477     - po_T.lp  - Inlet Total Pressure of LPT, bar
 910.76     - To_T.lp  - Inlet Total Temperature of LPT, K
 1.0382     - po_eT.lp - LP Turbine Exhaust Back Pressure, bar
 708.56     - To_eT.lp - LP 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 ¦ 54.0 ¦pist. bowl¦ 83.23   0.34   16.42   13.87    0.01   0.00
-------------------------------------------------------------------------
Sum of all sprays    % 100.¦ 64.88   1.71    5.99   27.40    0.02   0.00
=========================================================================
Evaporation constants  bi  ¦ 24864   5169   18675   15781   14712    112
=========================================================================
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: 2.05
   Ratio¦  Rs of piston bowl     2.68 ¦    Rs  ¦-by Razleytsev    : 2.05
____________________
Versions:     Kernel 20.03.10;  RK-model 03.03.10;  NOx-model 02.04.10
```





Injection and HRR

During simulations of the z-engine working process over the whole operating map the necessity of intake duration control was discovered. The optimization of the valve timing at every operating point has been done. The Air mass flows thorough the intake port as functions of the crank angle at different intake durations are presented in the Fig. 1.1. for operating mode of BMEP = 26 bar @ 1500 RPM.

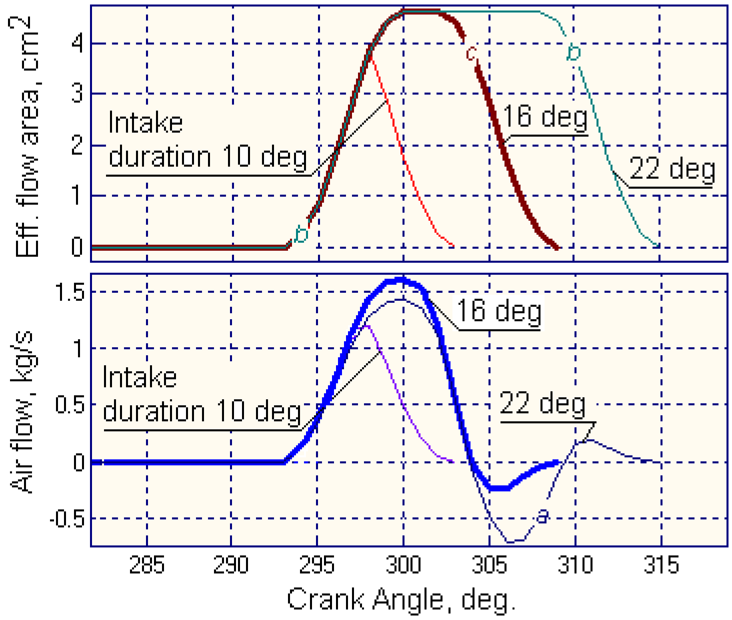


Figure 1.1. Air mass flows thorough the intake port vs. crank angle at different intake durations at BMEP = 26 bar @ 1500 RPM.

The maximum volumetric efficiency takes place if intake duration is 16 deg. Optimum value of the intake opening is the same over the whole operating map and is 112 deg. after BDC. The optimization of intake duration was carried out for all 5 operating modes shown in the table 2 as well as in tables 3 – 7. The optimum intake duration as a function of RPM is presented in the Fig. 1.2.

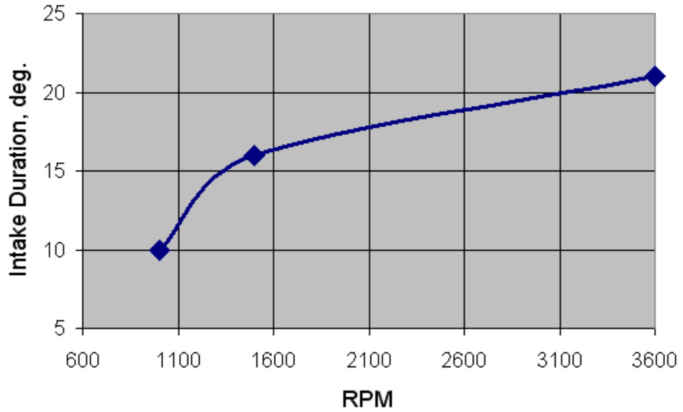


Figure 1.2. The optimum intake duration as a function of RPM.

Map of the SFC of z-engine in comparison with the same map of conventional 4 stroke DI diesel is presented in Fig. 1.3.

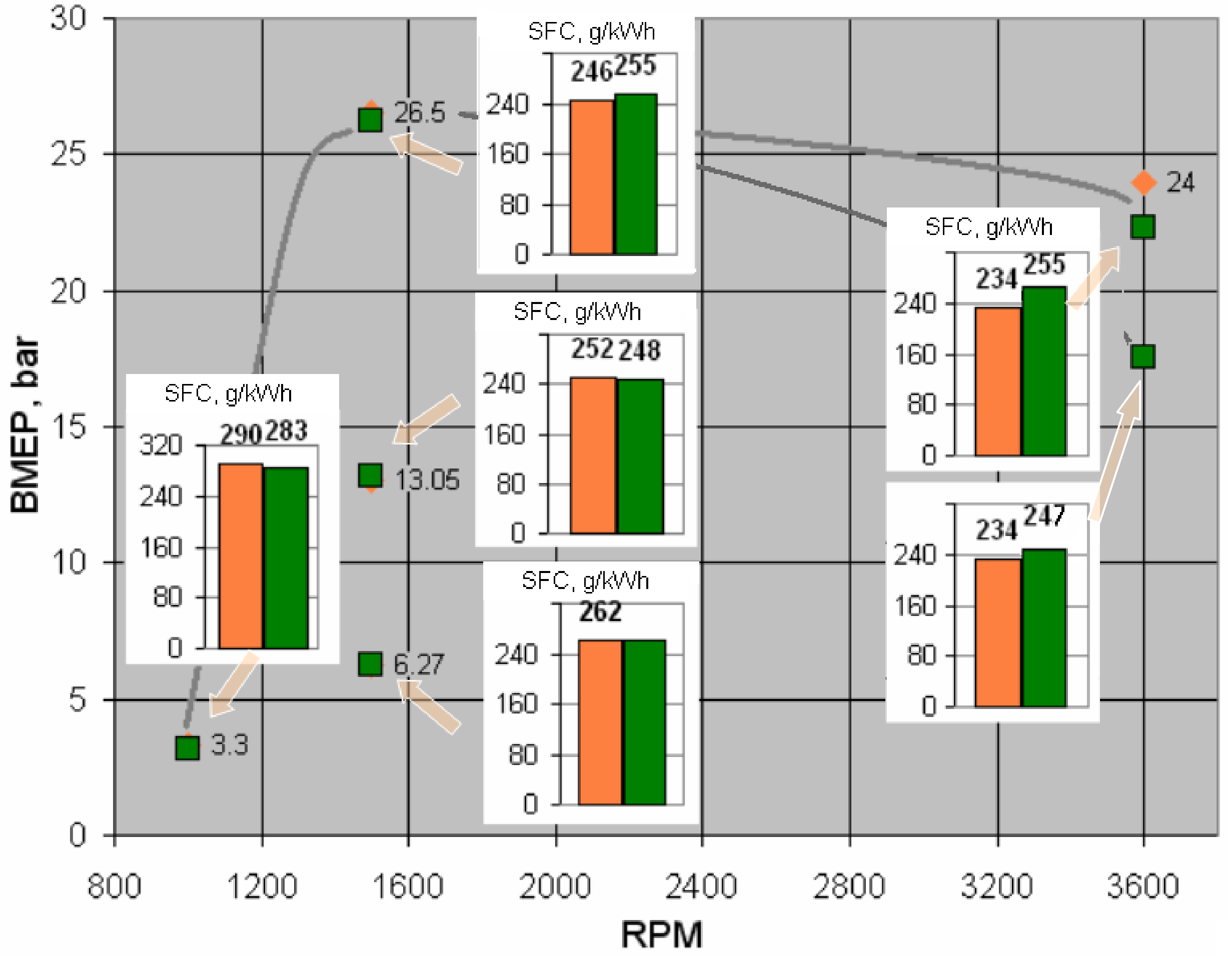


Figure 1.3. Map of the SFC of z-engine and of conventional 4 stroke DI diesel.

Analysis of obtained data illustrates some advantages of the z-engine concept in SFC at the part loads. But at the high power and torque z-engine has worse fuel efficiency than conventional 4 stroke DI diesel. The Specific Fuel Consumption as a function of BMEP at RPM=1500 is presented in the fig. 1.4.

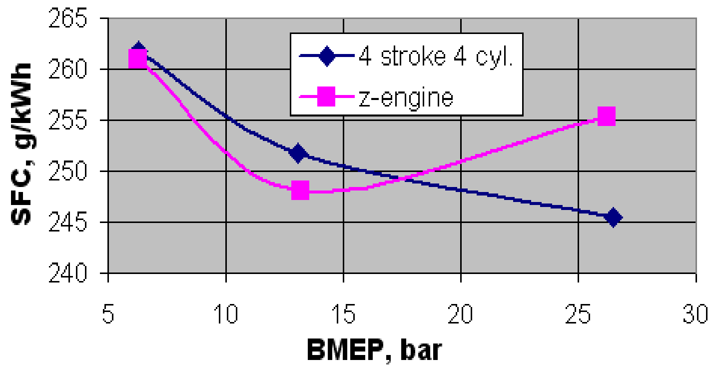


Figure 1.4. The Specific Fuel Consumption as a function of BMEP at RPM=1500

The reason of high SFC at the full load and maximum torque is large losses during intake. The more boost pressure the more losses due to sharp expansion of the intake flow in cylinder after the intake port. The power required to drive the piston compressor is about 22-25 % of piston engine capacity (Tab. 2). The more losses due to intake with large pressure drop the more power is required to drive the supercharger and more fraction of this energy is wasted.

The Air/Fuel eq. ratio and Bosch Smoke Number (BSN) are presented on the map of Fig. 1.5. Both figures 1.3 and 1.5 illustrated z-engine parameters degradation at the maximum power point (BMEP=24 bar @ 3600 RPM): SFC grows, BSN = 2.7. Last is unallowable.

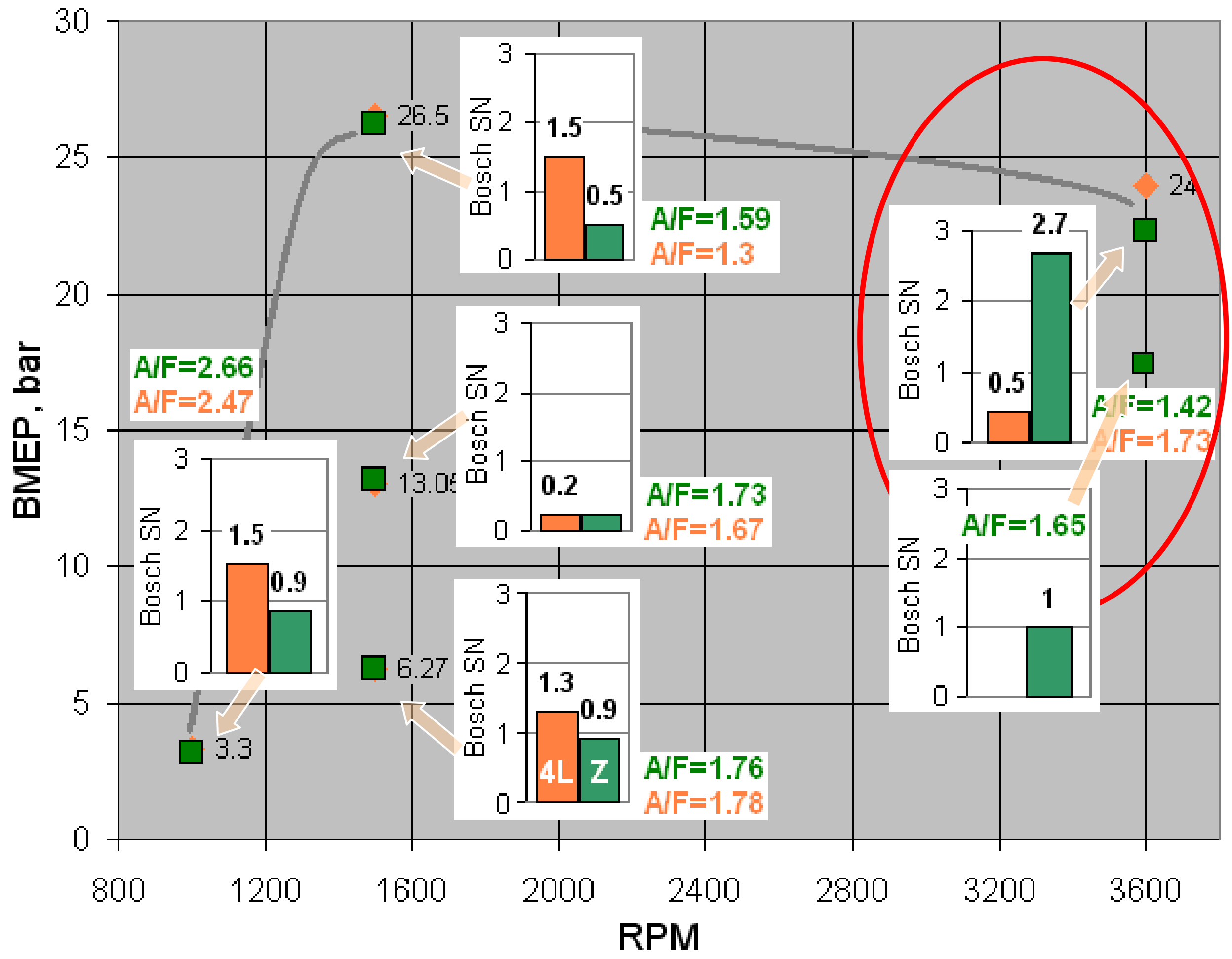


Figure 1.5. Map of the BSN and A/F eq. ratio of z-engine and of conventional 4 stroke DI diesel.

Due to very high level of the BSN at the maximum power operating point it seems necessary to decrease maximum z-engine power from 75 kW down to 60 kW @ 3600 RPM. In that case at the maximum power the BSN = 1 and SFC = 247 g/kWh (last exceeds conventional engine in 5.5 %).

The curves of maximum cylinder pressure vs. BMEP are presented in the Fig. 1.6.

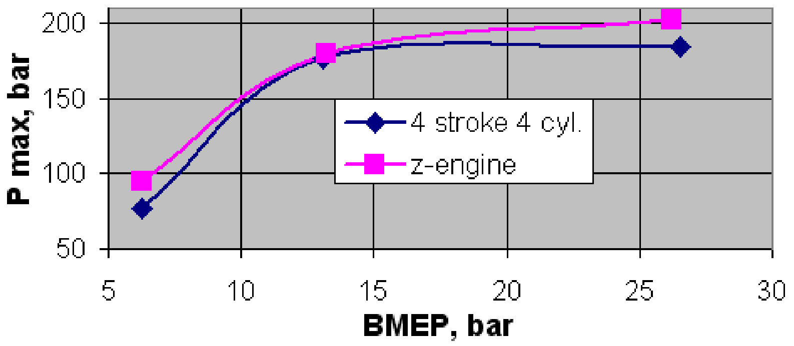


Figure 1.6. The maximum cylinder pressure vs. BMEP at RPM=1500.

Fig. 1.6. illustrates the combustion in the z-engine and conventional 4 stroke DI diesel engine takes place at about same pressure level. But the temperature behavior is different radically. The temperature of TDC and maximum temperature are presented in the Fig. 1.7.

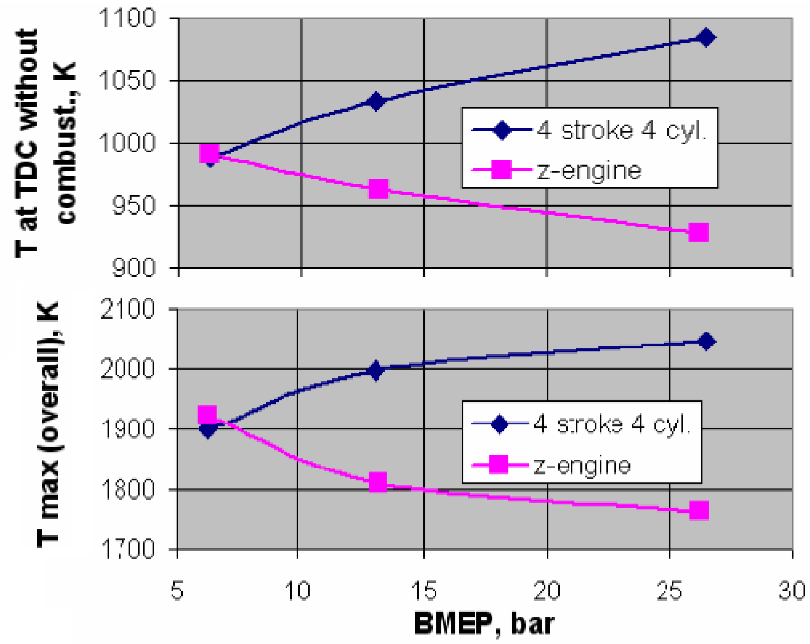


Figure 1.7. The temperature of TDC and maximum cylinder temperature as functions of BMEP.

The reduction of the TDC temperature at the larger BMEP is a result of internal cooling of the cylinder gas by larger portion of cold fresh charge. So Residual Gas Mass Fraction x_r decreases at the larger BMEP (Tab. 2.) These unusual temperature behaviors together with large overall x_r level result in radical NOx decreasing. Map of the NOx emission [g/kW h] of z-engine in comparison with the same map of conventional 4 stroke DI diesel is presented in Fig. 1.8. These data show radical decreasing of the NOx emission of the z-engine in comparison with conventional DI diesel. In the working region (cases #3 and #4) there are NOx = 0.5 – 0.7 g/kWh. It seems very good. The combustion process was optimized for minimum values of SFC because the NOx emission is very law at all operating points.

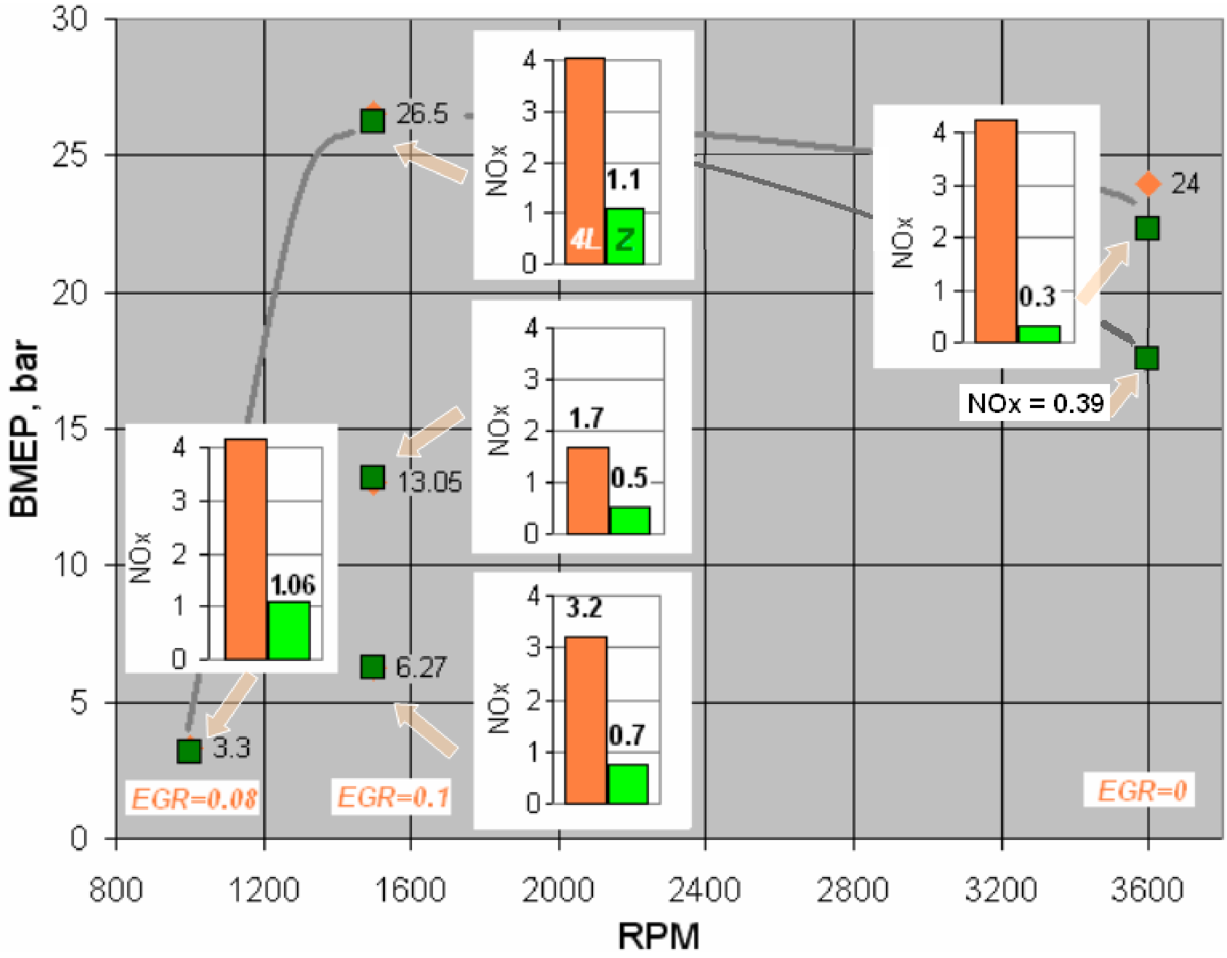


Figure 1.8. Map of the NOx emission [g/kW h] of z-engine in comparison with the same map of conventional 4 stroke DI diesel having EGR=0.1 everywhere except maximum power point where EGR=0.

The curves of NOx emission vs. BMEP at the RPM=1500 are presented in the Fig. 1. 9.

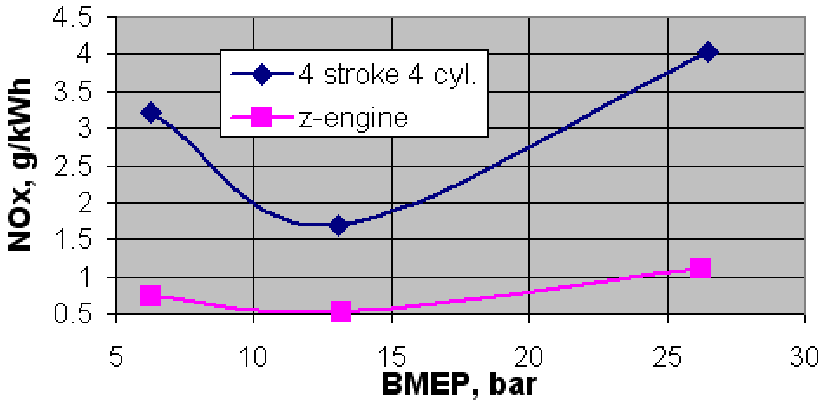


Figure 1.9. NOx emission vs. BMEP at the RPM=1500

The reason of small NOx emission of z-engine is a large Residual Gas Mass Fraction x_r (internal EGR) small temperature of combustion (temperature in the combustion zone). Comparison of these parameters for z-engine and for conventional DI diesel is presented in the Tab. 8. Combustion in the z-engine takes place at the temperatures being less than 2400 K. It is just what temperature when thermal NOx start to be formed intensively.

Table 8.

Comparison of Temperature of Combustion and Residual Gas Mass Fraction x_r for z-engine and for conventional DI diesel

RPM	**BMEP**	4 stroke DI diesel		z-engine	
		T combust	x_r	T combust	x_r
1000	3.34	**2486**	**0.132**	*2270*	**0.311**
1500	6.327	***2475***	**0.146**	*2313*	**0.302**
1500	13.2	***2537***	**0.144**	*2374*	**0.263**
1500	26.1	***2402***	**0.134**	*2350*	**0.163**
3600	17.4	***2700***	**0.03**	*2088*	**0.188**

Conclusions

1. Computational thermodynamic research of z-engine performed in the comparison with conventional engine having same dimensions shows advantages of z-engine concept in the following items:
   a) Downsizing of DI diesel engine is possible with conservation of engine power and torque.
   b) Z-engine has smaller Specific Fuel Consumption at low capacity and larger SFC at max. torque and max power points.
   c) Z-engine has smaller Soot emission (0.2-0.9 Bosch SN) at working range of engine speed, and larger Soot emission (up to 1. Bosch SN) at max Load point.
   d) Z-engine has extra low level of NOx emission even without external EGR system: mainly NOx<0.7 g/kWh, and only at idling and max torque NOx ~ 1.1 g/kWh. The small NOx emission is provided by low temperature in the engine cylinder before and during combustion, and relatively high internal EGR.
   e) To provide suitable engine performance z-engine should have:
      - VVA system for intake valves controling valve closing;
      - Variable turbine geometry turbocharger;
      - High pressure Common Rail fuel injection system for split injection;
      - Effective supercharger with Constant Pressure Ratio (although future research may show efficiency of Variable Pressure Ratio Supercharger).

   f) Noted conclusions are confirmed by usage the well tested professional software DIESEL-RK intended for full cycle thermodynamic piston engine simulation and optimization. The software has modern advanced models for diesel combustion and emission simulation.
2. Low production cost is predicted due to smaller number of engine parts.

3. High BMEP and good part load efficiency of the z-engine were validated at simulations and optimization of engine parameters in comparison with traditional 4 stroke 4 cylinder DI diesel engine.
4. Good transient behavior is anticipated due to usage the supercharger and two stroke cycle. Z-engine concept.

2. General analysis of the z-engine design.

The original design of the z-engine developed by Aumet OY is presented in the Fig. 2.1.

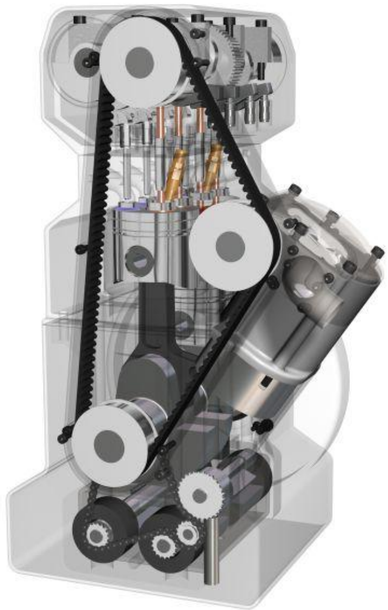
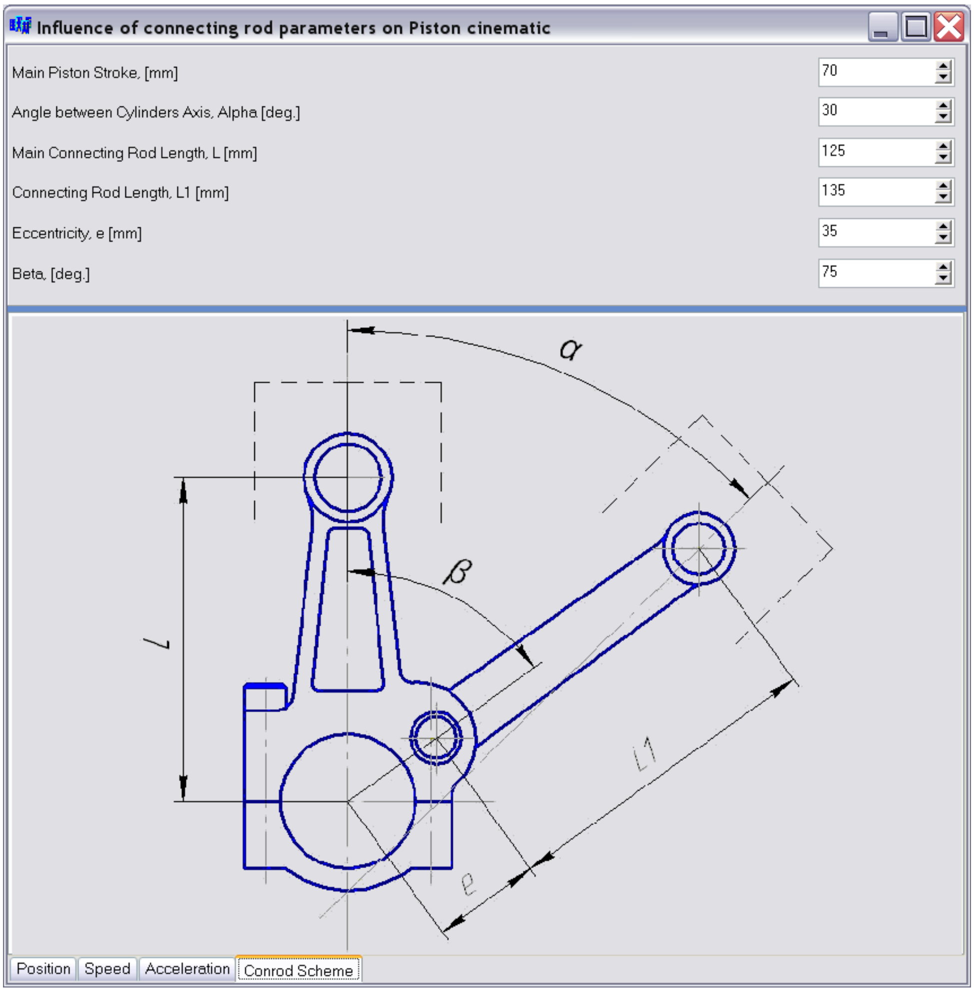


Figure 2.1. The original design of the z-engine developed by Aumet OY.

One has two in line cylinders and piston compressor where axis of supercharger cylinder has inclination angle 30 deg. To estimate the kinematics and dynamic of the compressor crank mechanism with articulated (link) rod the special software was developed by author of this work. The equations being used for main and linked pistons motion (velocity and acceleration) calculation are published in [1]. The main dimensions of crank and connecting rods being input data for the program were taken from the Aumet Oy drawings. The screenshots of the program are presented in the Fig. 2.2.

Calculated data show the compressor piston stroke is larger than diesel piston stroke and is 78.2 mm (diesel piston stroke is 70 mm). The original Aumet Oy z-engine has Lanchester Balancing Mechanism to balance the forces of reciprocating masses. But if compressor piston moves in the inclined plain the noted mechanism



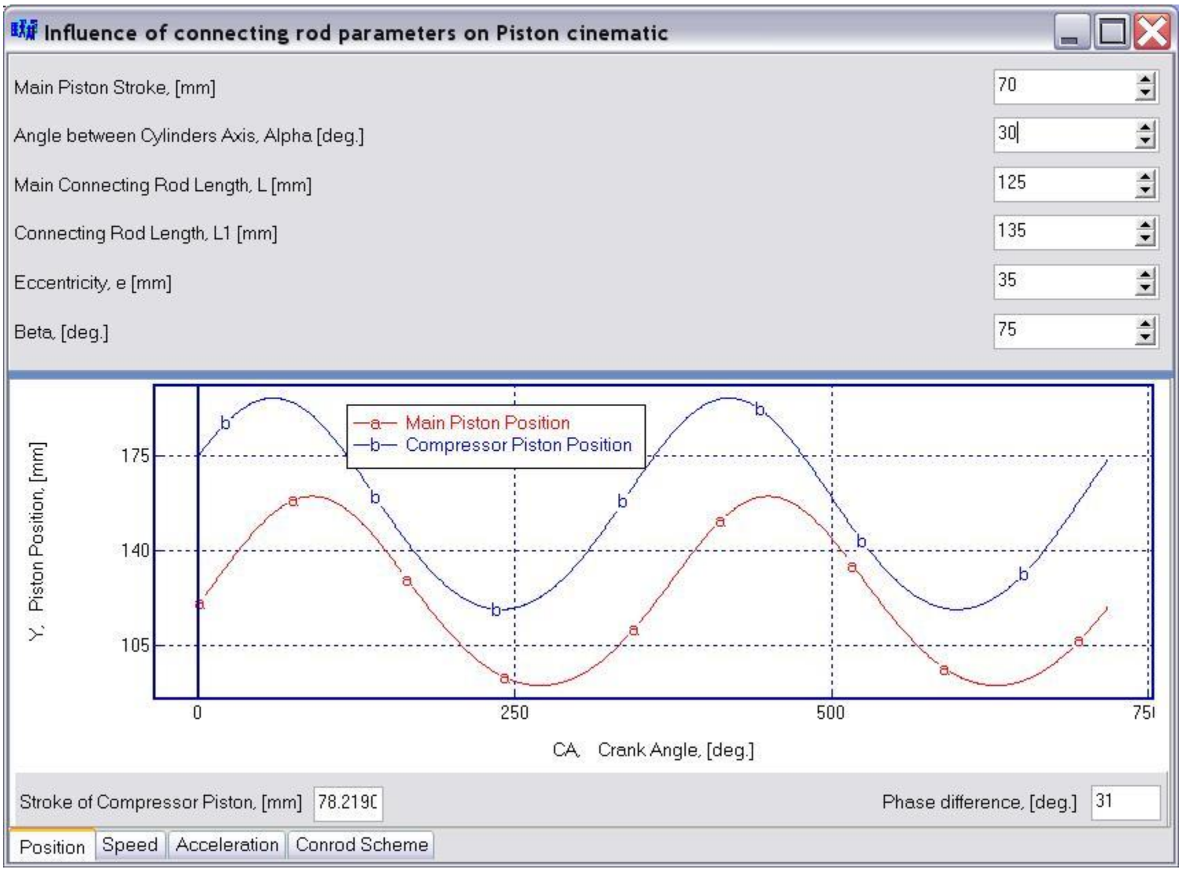


Figure 2.2. The screenshots of the program for crank mechanism analysis.

can not completely balance these forces. To make the z-engine balancing easy and more economical there was made decision to use the compressor being in line with working cylinders of diesel, Fig. 2.3. To balance the first order forces of rotating

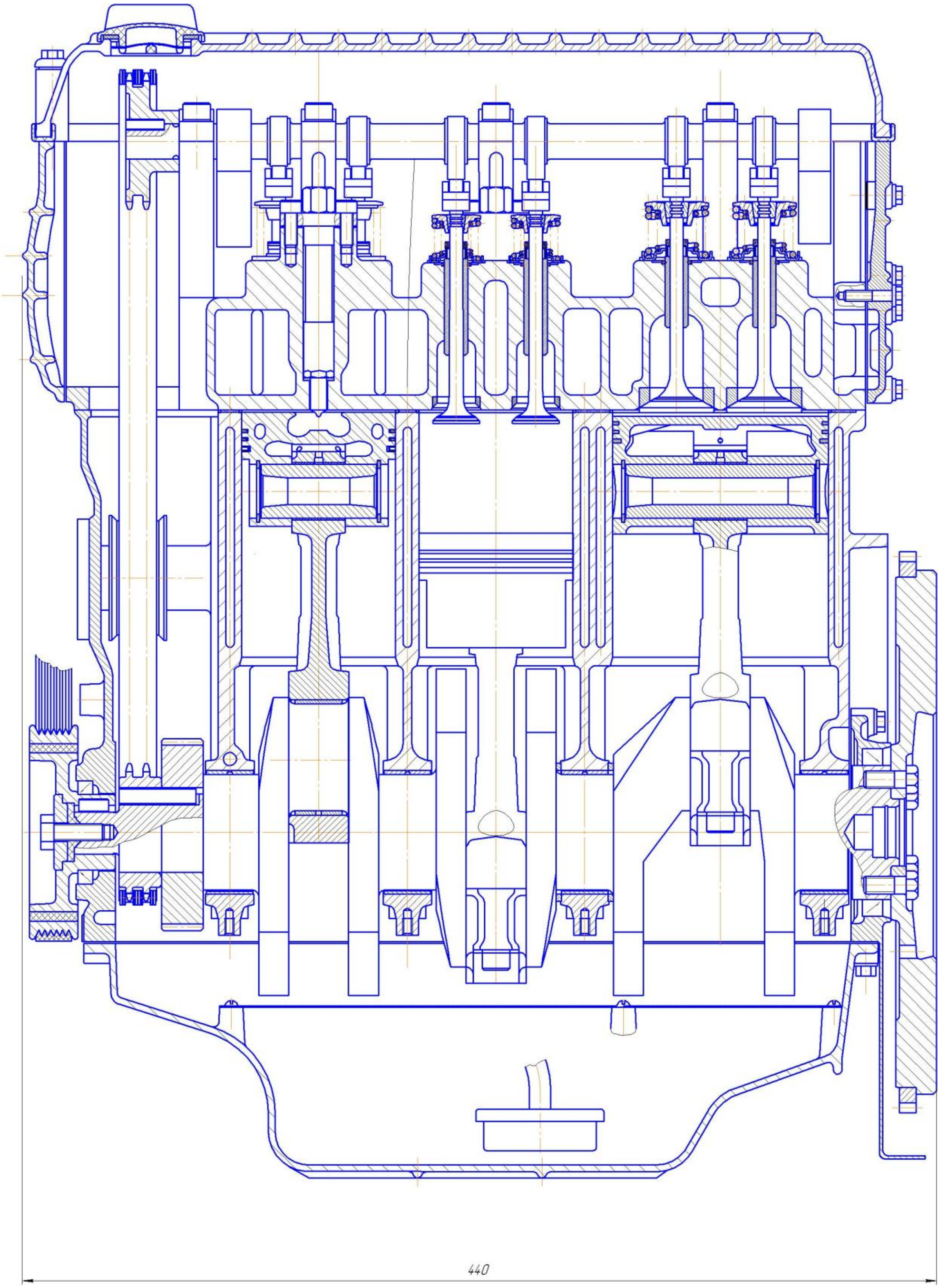


Figure 2.3. Longitudinal section of the z-engine with piston compressor.

masses of diesel parts and compressor parts the counterweights on the crankcheeks are used. To balance the forces of reciprocating masses the counterweights on the camshafts are used. Engine should have 2 cam shafts. The compressor is controlled by the same cam shafts as engine cylinders. It allows to keep the minimum number of bearings and minimum losses in the train. Due to large diameter of the intake cams the counterweights on the cam shaft will not increase the z-engine dimensions. The cross section of the z-engine is presented in the Fig. 2.4.

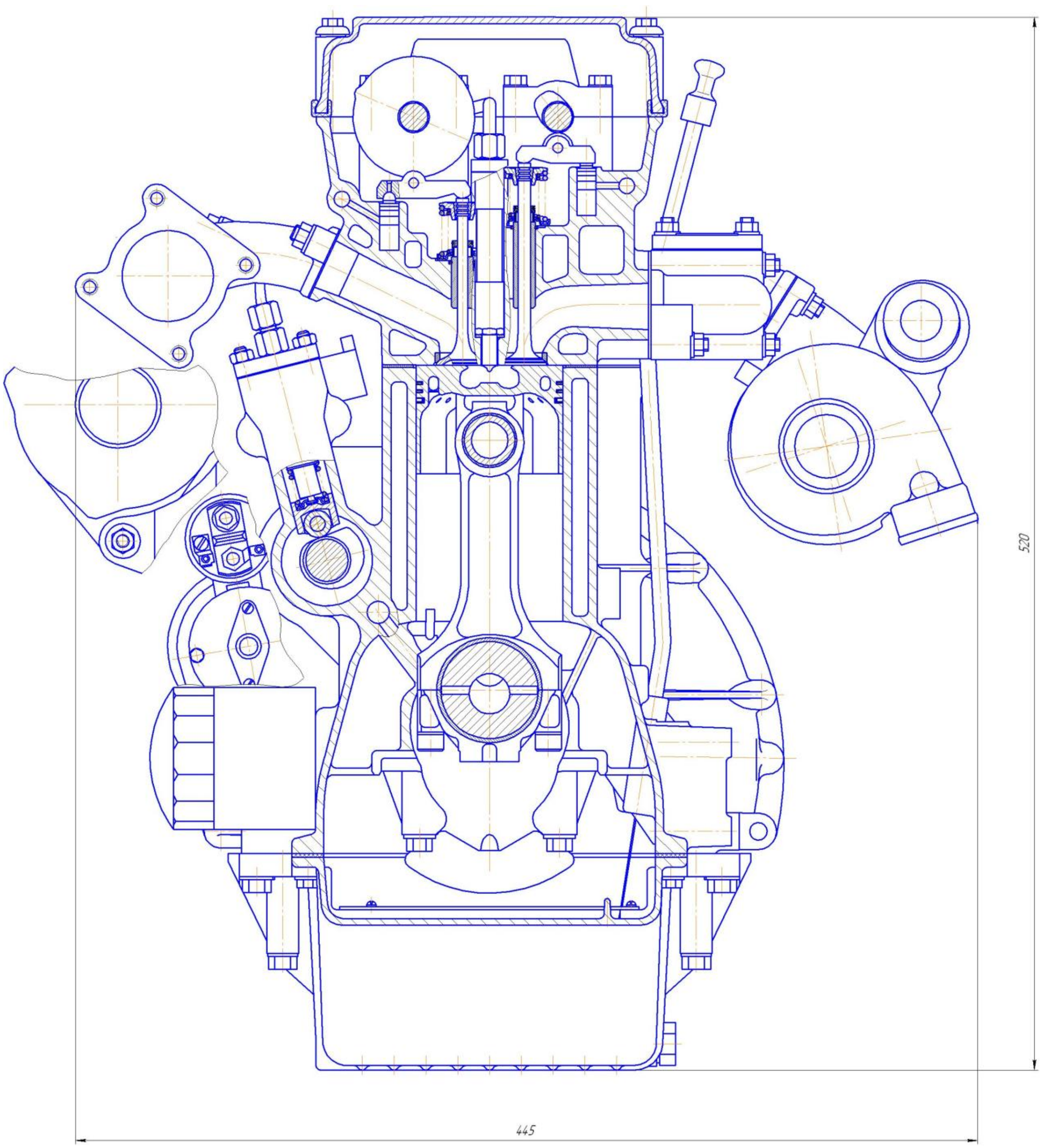


Figure 2.4. Cross section of the z-engine.

Calculation of the main bearings.

At calculation of the main bearing it is assumed the lubrication oil layer has to bear all forces from the crank shaft and thickness of the layer should be larger than total size of asperities of both surfaces and deflection of the shaft. Method of allowed pressure is one of the easiest but is widely used. The bearing inserts from brand name companies usually are working well if total pressure does not exceed 50-60 MPa. So in this work it is assumed the maximum allowable pressure is [p] = 60 MPa.

Input data:

- Diesel cylinder diameter $D := 0.072 \cdot m$
- Crank radius $R := 0.035 \cdot m$
- RPM and angular velocity $n := 1500 \cdot \frac{1}{min}$ $\quad \omega := 2 \cdot \pi n = 157.08 \frac{1}{s}$
- Maximum cylinder pressure $P_z := 20 \cdot 10^6 \cdot Pa$
- Length of main bearing $l_1 := 0.028 \cdot m$
- Diameter of main bearing $d_1 := 0.054 \cdot m$
- Mass of reciprocating moving parts $M_{recip} := 1.396 \cdot kg$

1) Force acting on the main bearing at TDC:

$$P_{max} := \left[P_z \cdot \left(\frac{\pi \cdot D^2}{4} \right) - M_{recip} \cdot R \cdot \omega^2 \right] \qquad P_{max} = 8.022 \times 10^4 N$$

2) Pressure in the main bearing at TDC:

$$p := \frac{P_{max}}{d_1 \cdot l_1} \qquad p = 5.306 \times 10^7 Pa$$

Conclusion: The maximum pressure acting in the main bearing does not exceed the adopted pressure: $p < [p]$.

Calculation of the piston compressor parameters.

The aim of this calculation was the determination of the piston compressor pressure ratio and diameter of it cylinder. It is supposed the compressor parameters are corresponded with maximum torque operating point with RPM=1500.

The main equations are taken from [3]

It is accepted the piston compressor has same stroke as engine cylinders and is S_1 = 0.070 m.

Parameters of air:

- adiabatic exponent γ = 1.4 ;
- gas constant R = 287 J/kg/K;
- ambient pressure P_0 = 101300 Pa.

Total temperature in the compressor inlet	T_1 = 318 K.
Total pressure in the compressor inlet	P1 = 423700 Pa
Required pressure after compressor	P2 = 1801000 Pa
Mass air flow rate	m_{iar} = 0.05325 kg/s
Polytrophic exponent at compression	n = 1.35
Polytrophic exponent at expansion	n_p = 1.2
Factor of air heating in the compressor intake (0.9-0.94)	λ_t = 0.92
Factor accounting the leakage at compression (0.95-0.98)	λ_Γ = 0.97
Rated dead volume Vc1/Vh1 (0.025 ... 0.6)	a = 0.04

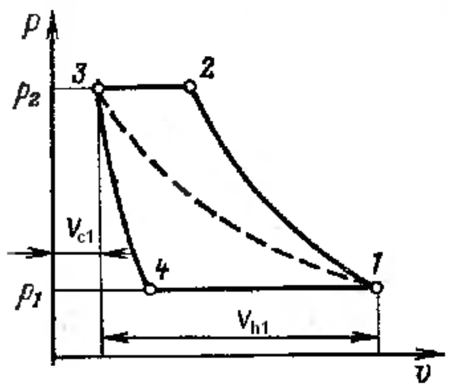


Figure. 2.5. P-V diagram of the piston compressor.

1. Air density at the beginning of compression ρ_1 and difference between V_1 and V_4 rated to reciprocating volume V_{h1}

$$\rho_1 := \frac{P_1}{R \cdot T_1} \qquad \rho_1 = 4.642 \quad \text{kg/m3}$$

$$V_{14v} := \left[1 - a \cdot \left[\left(\frac{P_2}{P_1} \right)^{\frac{1}{n_p}} - 1 \right] \right] \cdot \lambda_T \cdot \lambda_T \qquad V_{14v} = 0.809$$

2. Air volume in the point #4 rated to reciprocating volume V_{h1}

$$V_{4v} := a \cdot \left(\frac{P_2}{P_1} \right)^{\frac{1}{n_p}} \qquad V_{4v} = 0.134$$

3. Air temperature in the point #2

$$T_2 := T_1 \cdot \left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} \qquad T_2 = 462.744 \quad \text{K}$$

4. Required delivery of the compressor (difference between points #2 and #3) Air mass corresponded with moment when cylinder pressure is equal P_2

$$m_1 := \frac{60 \cdot m_{air}}{2RPM} \qquad m_1 = 1.065 \times 10^{-3} \quad \text{kg}$$

$$V_{23} := \frac{2 \cdot m_1}{\frac{P_2}{R \cdot T_2}} \qquad V_{23} = 1.571 \times 10^{-4} \quad \text{m}^3$$

5. Required compressor delivery rated to V_{h1}

$$V_{23v} := \left(\frac{P_1}{P_2} \right)^{\frac{1}{n}} \cdot \left(V_{14v} + V_{4v} \right) - a \qquad V_{23v} = 0.283$$

6. Reciprocating volume of the compressor and piston diameter D_1.

$$V_{h1} := \frac{V_{23}}{V_{23v}} \qquad V_{h1} = 5.557 \times 10^{-4} \ \mathrm{m^3}$$

$$D_1 := \left(4 \cdot \frac{V_{h1}}{\pi \cdot S_1}\right)^{\frac{1}{2}} \qquad D_1 = 0.101 \ \mathrm{m}$$

7. Compressor pressure ratio ε_1

$$V_{c1} := a \cdot V_{h1} \qquad V_{c1} = 2.223 \times 10^{-5} \ \mathrm{m^3}$$

$$\varepsilon_1 := 1 + \frac{V_{h1}}{V_{c1}} \qquad \varepsilon_1 = 26$$

8. Discharge temperature T_2 and maximum cylinder pressure P.

$$P := \pi \cdot \frac{{D_1}^2}{4} \cdot P_2 \qquad P = 1.429 \times 10^4 \ \mathrm{N}$$

See item #2 $\qquad T_2 = 462.744$ K

9. Compressor power if isothermal efficiency η_t = 0.79 (0.65 - 0.85) and mechanical efficiency η_t = 0.9 (0.85 - 0.93)

$$N := \frac{m_{air} \cdot R \cdot T_1 \cdot \ln\left(\frac{P_2}{P_1}\right)}{1000 \cdot \eta_t \cdot \eta_m} \qquad N = 9.89 \ \mathrm{kW}$$

Conclusion:

The diameter of compressor piston should be equal 101 mm.

The compression ratio should be 26.

The power to drive the compressor is 10 kW.

Engine design general description

Crankcase.

Engine crankcase consists of several parts being cast of iron. The solid side walls with transverse baffles give the necessary rigidity of the crankcase.

Crankshaft bearings are suspended-type. They consist of steel base and thin bronze layer. The cylinder block and cylinder head are fastened with several steel stud-bolts. On the left and right sides of the crankcase there are two longitudinal channels for oil feed to the bearings of crankshaft, camshaft bearings and axes of valve pushers.

Cylinders.

The upper face of cylinder block and bottom plane of cylinder head are sealed by copper gasket. The cylinders are machined directly in the crankcase.

Pistons.

The pistons are solid and cast of steel. The piston skirt is domed and has elliptical shape. The pistons have cast-in cooling gallery. The cooling oil is delivered into gallery from special injector. The pistons have two compressing rings and one oil control ring.

Piston pins.

Piston and connecting rod are connected by piston pin, which pressed into the connecting rod. Axis displacement of piston pin is limited by circlips. Piston pin is made of chrome-nickel steel in the form of a hollow cylindrical rod, hardened carburizing and quenching.

Connecting rods.

The material of connecting rod is steel. Billet is obtained by stamping. The billet profile is I-section. Connecting rod cover is attached by two connecting rod bolts.

Crankshaft.

The material of crankshaft is 40CrNiMnAlN. Billet is obtained by stamping. Also, it is subjected to hardening nitriding and quenching high frequency currents. Crankshaft has holes for oil feeding. From one side the crankshaft has a sprocket for gearing oil and water pumps. For sprockets fixing a press fit and parallel keys are used.

The front main bearing of crankshaft is sealed with a rubber seal.

The thrust bearings fix the crankshaft against axis displacement.

Cylinder head.

The monolith cylinder head is used. Cylinder head includes seats for two intake and two exhaust manifolds and injector (one pair for engine cylinders and one pair for compressor). Port design is forked. The intake and exhaust manifolds are fixed to the end faces of cylinder head channels via stud bolts.

Bronze valve sleeves and cast iron valve seats are pressed in cylinder head.

Valve gear.

Valves are geared from two camshafts and rockers.

Hydraulic compensators are installed in cylinder head. They automatically fix heat clearances in valve mechanism. Oil enters under pressure in chamber below the plunger.

Hollow steel camshafts have four pillars. From axis displacement camshafts fixed with thrust flange.

Camshafts are geared by chain drive.

For sprockets fixing the press fit and parallel keys are used.

Valves material is austenitic steel. Head diameter of intake valve is 27 mm and exhaust valve – 24 mm. The angle of the working chamfer of exhaust valve is 45^0 and intake valve – 30^0.

The material of rockers is steel. They have spherical tip for steel valve.

Lubrication system.

The engine lubrication system uses wet sump. Oil under the pressure feeds crankpins and main bearings of the crankshaft, goes to the bearings of camshaft, rocker sleeves, compressors, etc. Lubrication system includes: oil pump, wet sump, filters, heat exchanger, oil channels in sump, cylinder block ducts, cylinder head ducts, oil valves, etc. Oil pump is geared by gearwheel on crankshaft, which fixed with key joint and press fit. Steel sump is fixed on bottom plane of cylinder block by bolts. Sump and cylinder block are sealed with rubber gasket. Crankcase gases from inside sump cavity entered into the cavity of untreated air filter.

Cooling system.

Cooling system uses antifreeze for heat exchange. Liquid circulation proceeds in two closed circuits, which provides by centrifugal pump. Water pump is located in front of the engine and geared with chain drive. Z-engine uses dual- circuit cooling system. The additional cooling system is used for piston compressor cooling.

Fuel system.

Fuel system consists of: fuel tank, fuel lines, filters, fuel pump, fuel-injection pump, accumulator, and two injectors with electronic control. On the maximum torque operating mode the double injection strategy is used, Tab. 4.

The Cross and Longitudinal section drawings of the z-engine are developed and attached as CAD documents and their small copies are presented in the Appendix.

3. Finite Element Analysis of the z-engine piston.

The original design of the z-engine piston developed by Aumet OY is presented in the Fig. 3.1. Piston has aluminum body and made of steel encapsulated combustion chamber.

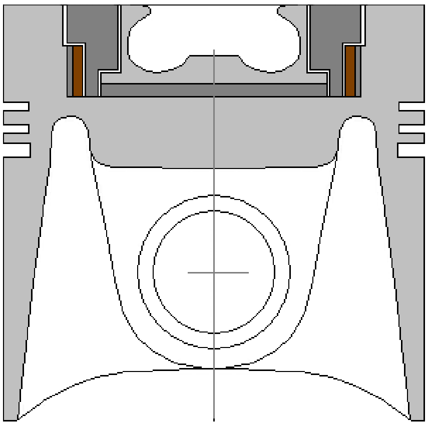


Figure 3.1. The original design of the z-engine piston developed by Aumet OY.

There was created the 3-D model of the piston Fig. 3.2. and boundary conditions Fig. 3.3. corresponded with maximum torque operating mode Tab.4.

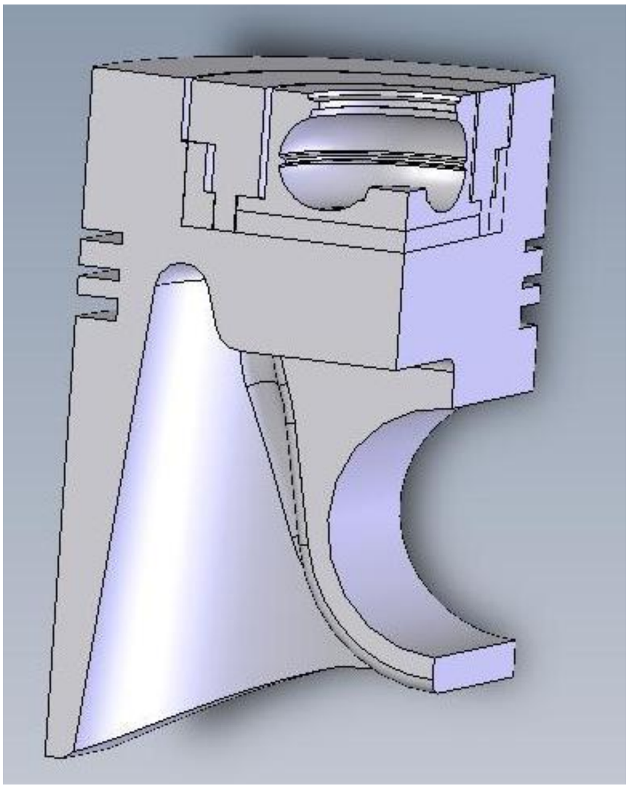


Figure 3.2. The 3-D model of the prototype piston

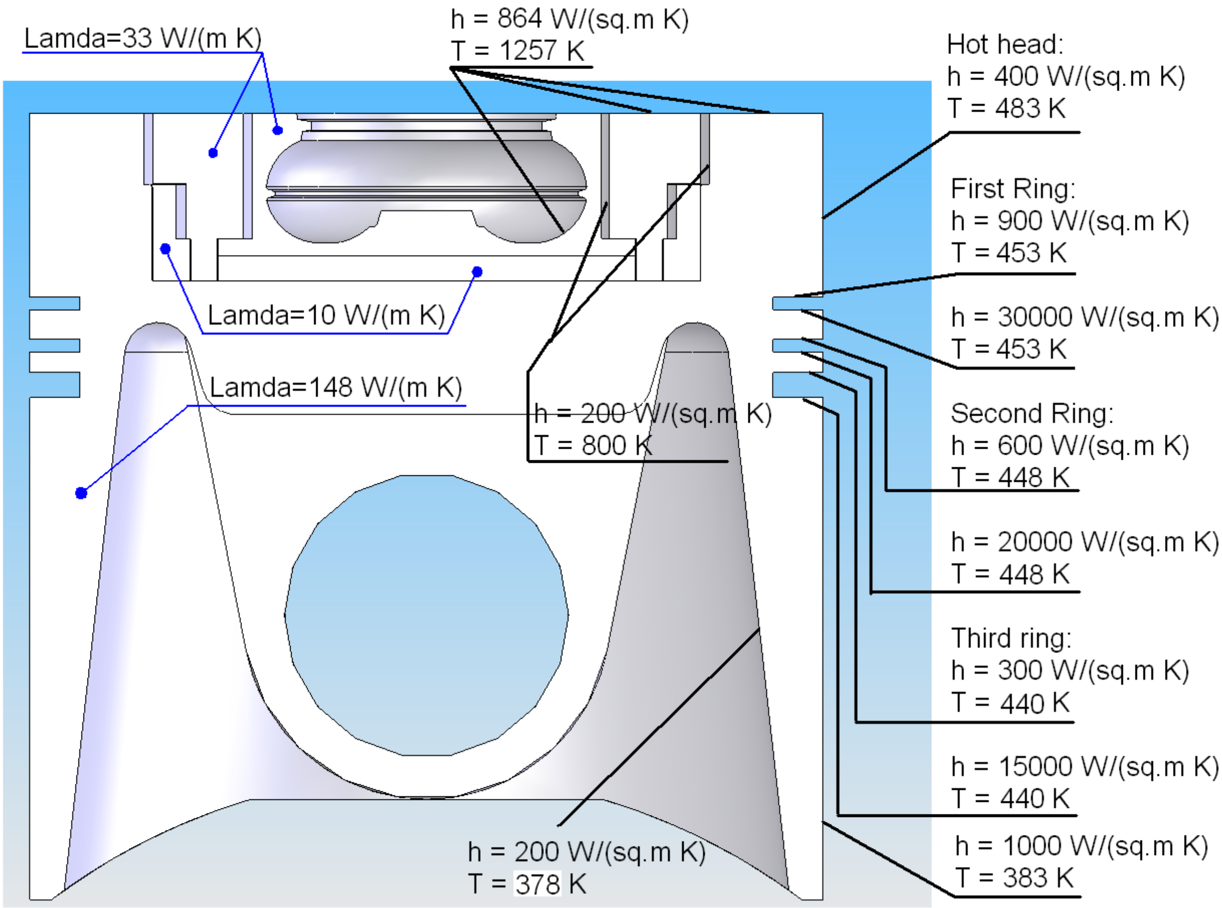


Figure 3.2. Boundary conditions for FEA corresponded with maximum torque operating mode, Tab. 6.

All FEA was done with ANSYS program [2]. This software is installed in the computer center of Bauman Moscow State Technical University.

The obtained temperature fields are presented in ^{0}C in figures 3.3, 3.4.

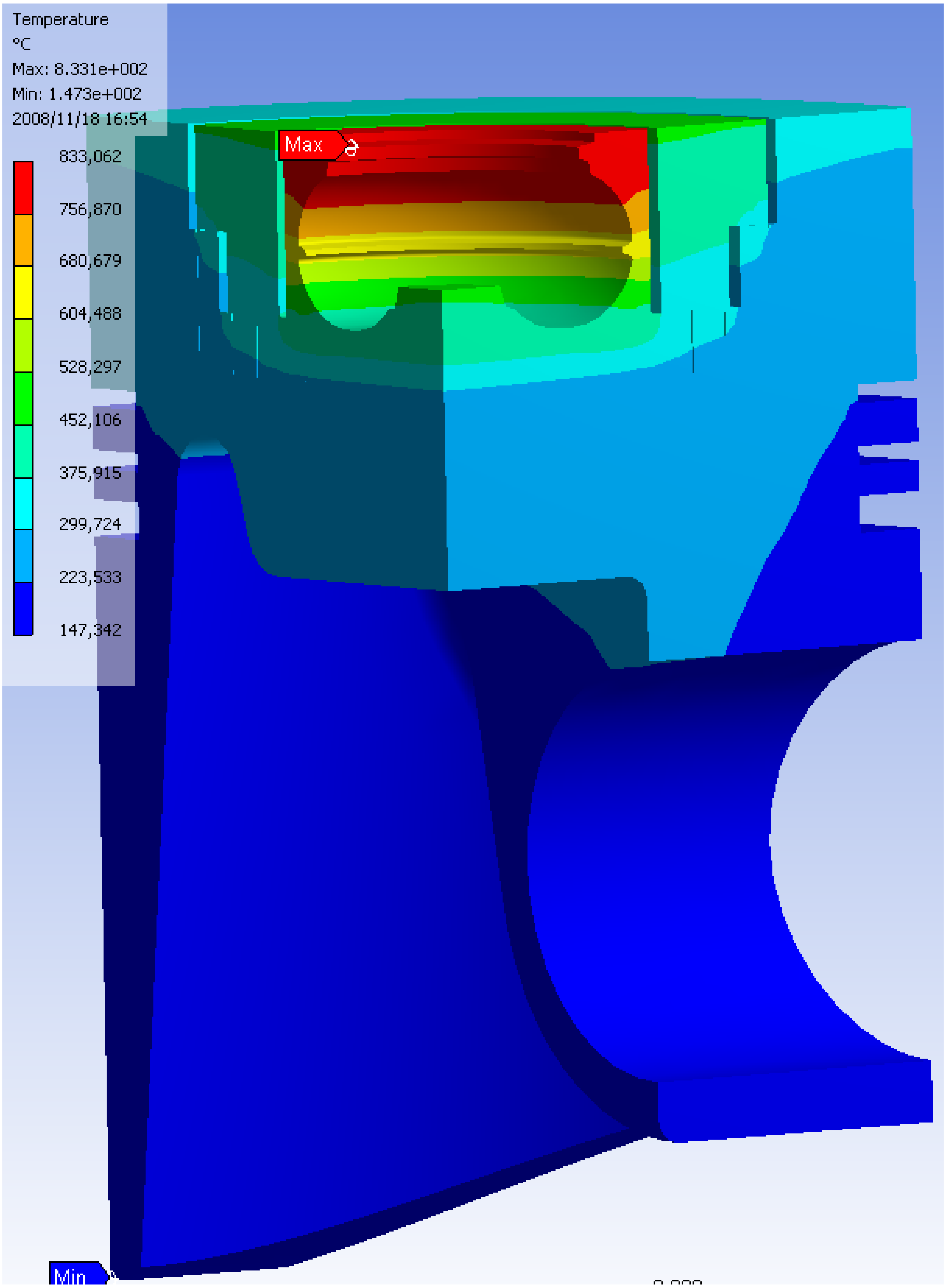


Figure 3.3. Temperature field in ^{0}C of prototype aluminum piston with encapsulated combustion chamber made of steel.

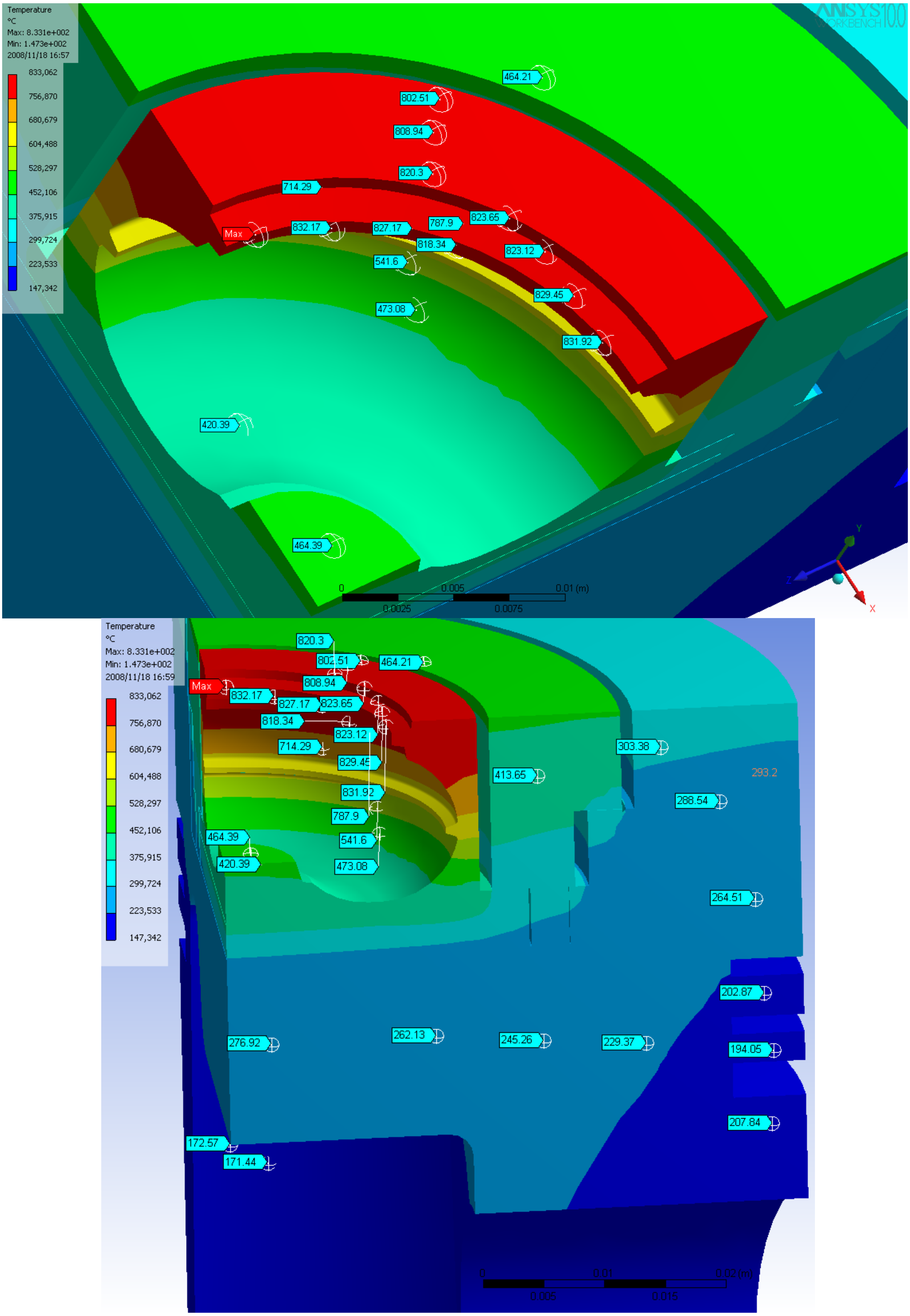


Figure 3.4. Temperature field in ^{0}C of prototype aluminum piston with encapsulated steel combustion chamber (large scale).

The analysis of obtained results shows unallowable high temperatures in the region of first piston ring and on the lip of piston bowl. First exceeds 223^0C (Fig. 3.3.) and second achieves 830 ^{0}C. To intensify cooling of the piston bowl and whole piston body there was investigated variant with cast-in steel combustion chamber with a gap being resistant to heat flow and radial thermal expansion as well as oil cooled piston skirt. All future investigations were done with oil cooled piston skirt so boundary conditions on this surface were changed to h=1200 W/m^{2}K; T=365 K. 3-D model and temperature stresses are presented in the Fig. 3.5. – 3.7. Overstressed zones in the bottom side of piston Fig. 3.7. appear due to intensive oil cooling. The stresses from gas forces were obtained for conditions of maximum cylinder pressure p_{max} = 200 bar, Fig. 3.8 – 3.9

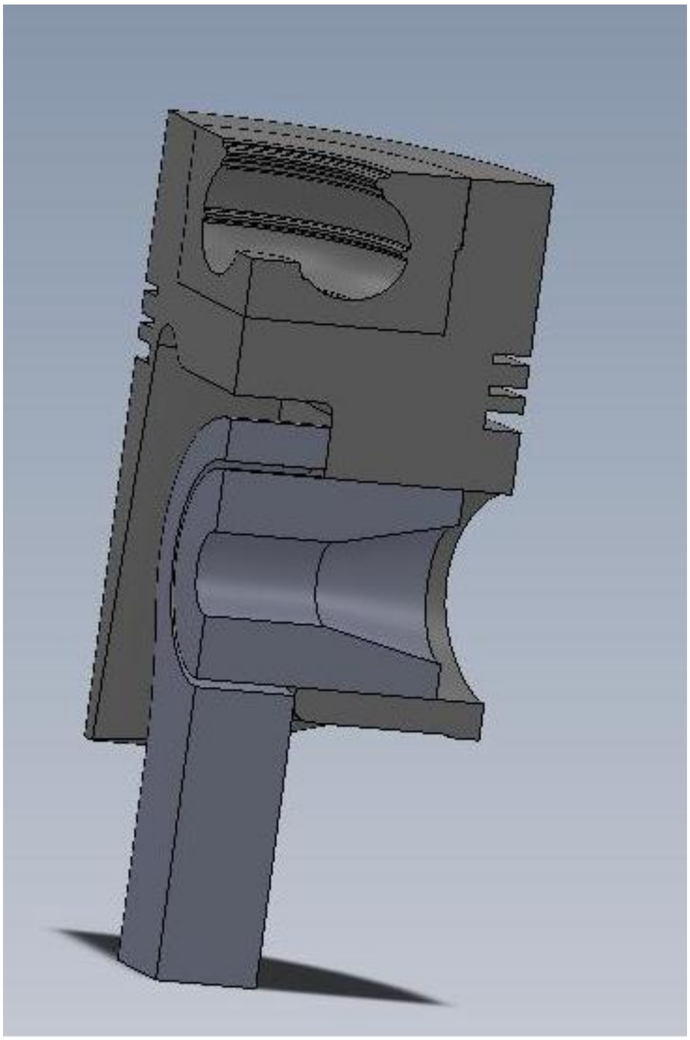


Figure 3.5. The 3-D model of the aluminum piston with cast-in steel combustion chamber, piston pin and connecting rod.

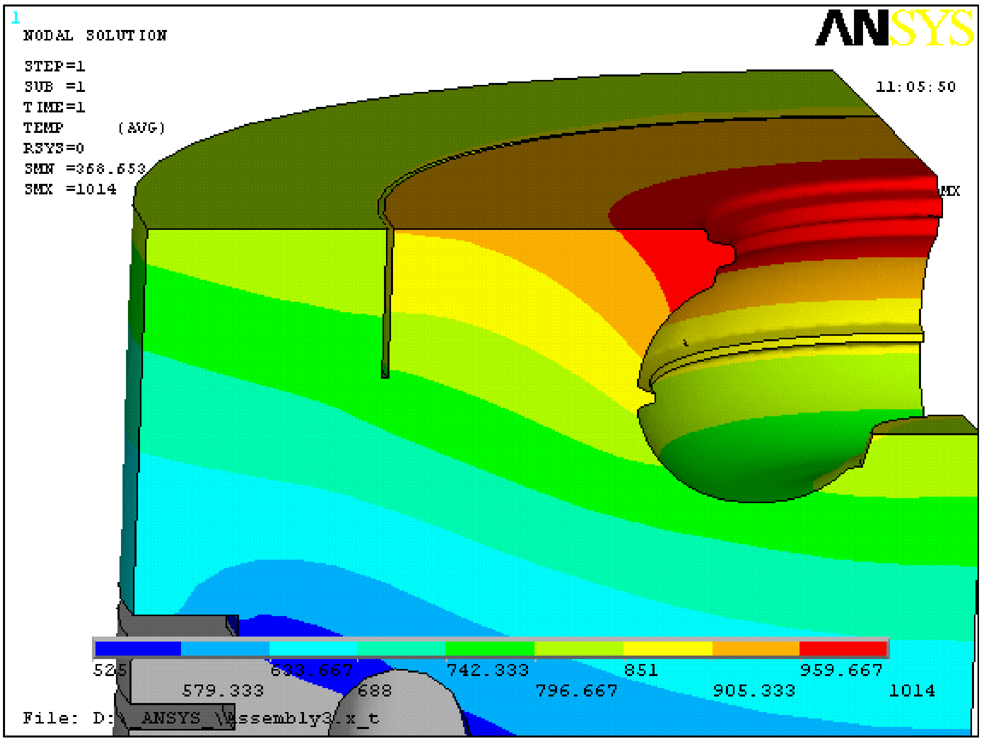


Figure 3.6. Temperature field in K of aluminum piston with cast-in steel combustion chamber.

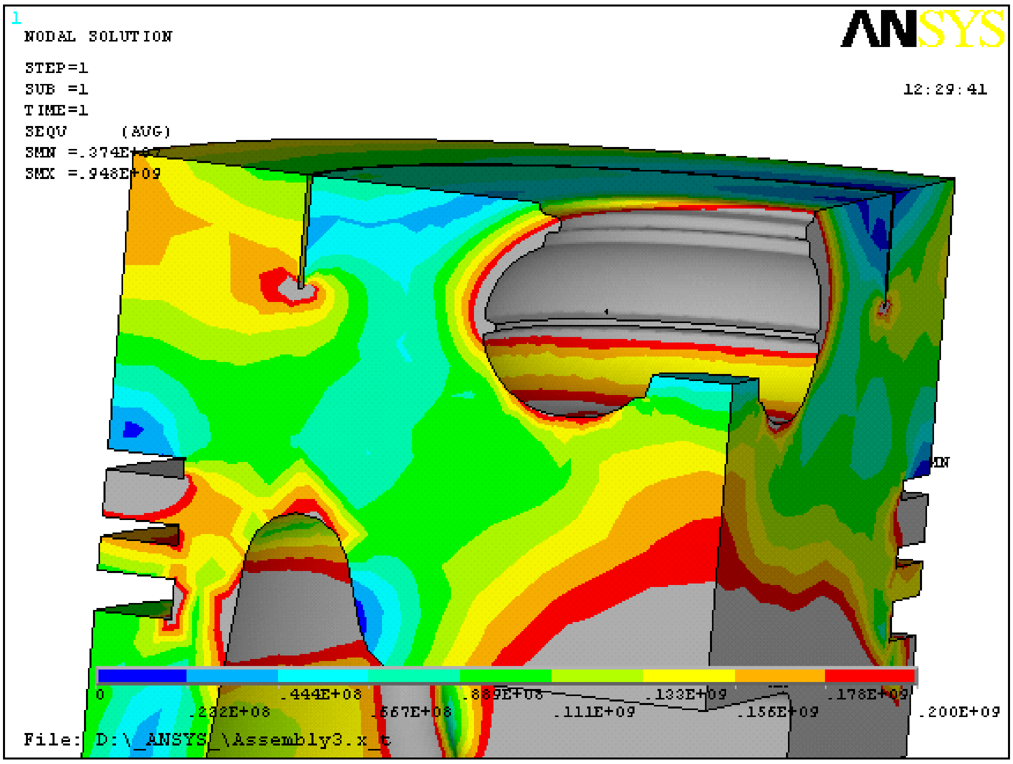


Figure 3.7. Temperature stresses in Pa of aluminum piston with cast-in steel combustion chamber. Unallowable level over 200 MPa (for aluminum) is colored by gray on red.

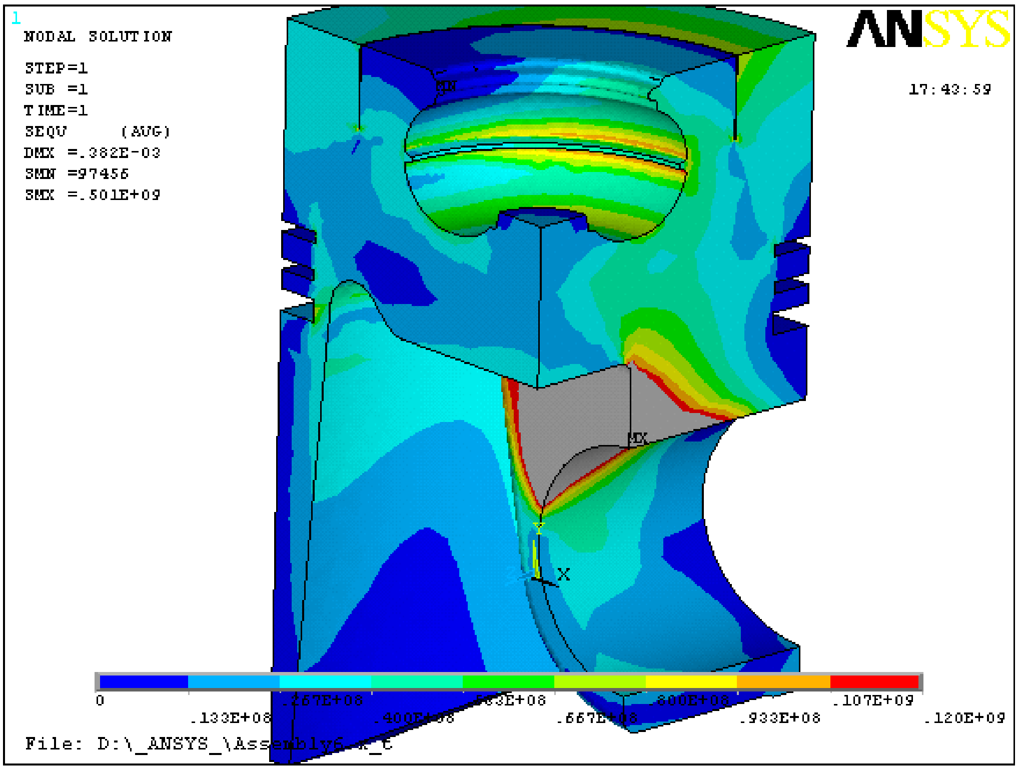


Figure 3.8. Gas force stresses in Pa of aluminum piston with cast-in steel combustion chamber. Unallowable level over 200 MPa (for aluminum) is colored by gray.

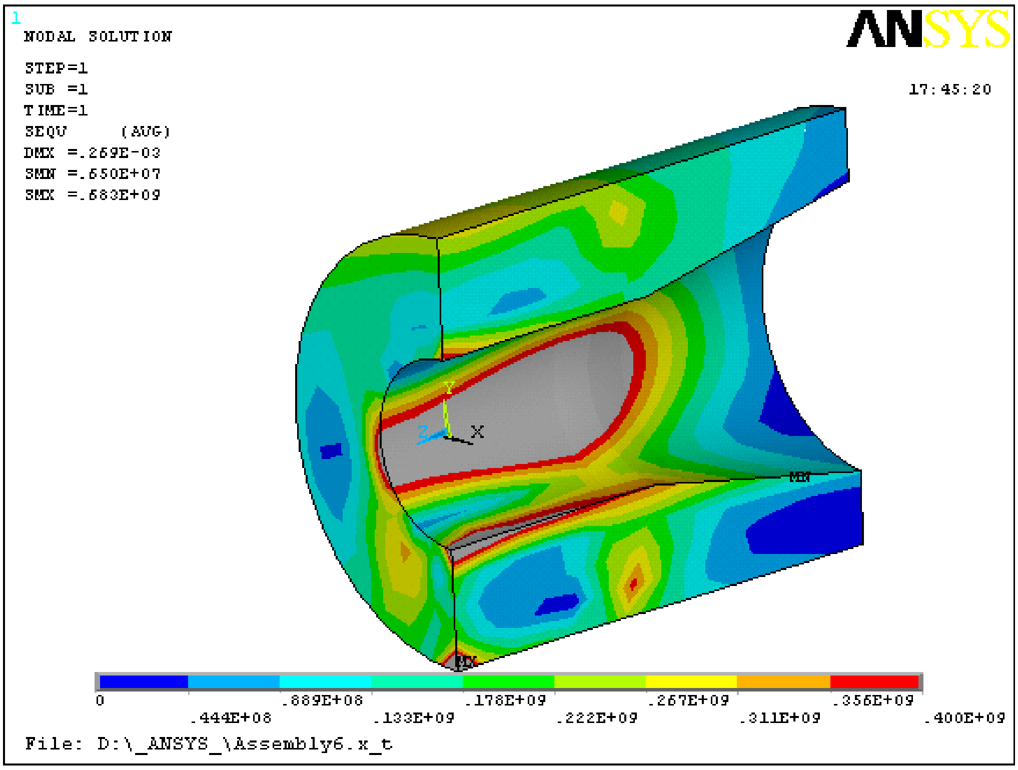
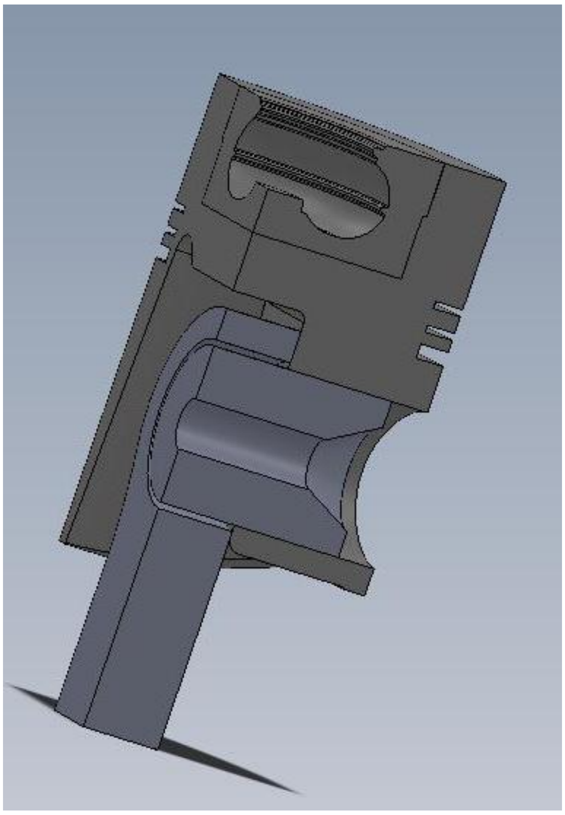


Figure 3.9. Gas force stresses in Pa of steel piston pin. Unallowable level over 400 MPa (for steel) is colored by gray.

The analysis of obtained data shows badness of aluminum piston as for the reason of too high temperatures in the region of first piston ring, as for the reason of too high stresses in the boss. The piston pin requires modification too.



On the next step the internal diameter of the piston pin was decreased and cone was done shorter. The piston body material was assigned as steel, Fig. 3.10.

Figure 3.10. 3-D model of the steel piston with cast-in combustion chamber, modified piston pin and connecting rod.

The stresses from gas forces were obtained for conditions of maximum cylinder pressure p_{max} = 200 bar, Fig. 3.11. The obtained maximum stress of 450 MPa in the small region of boss may be decreased by design improvement.

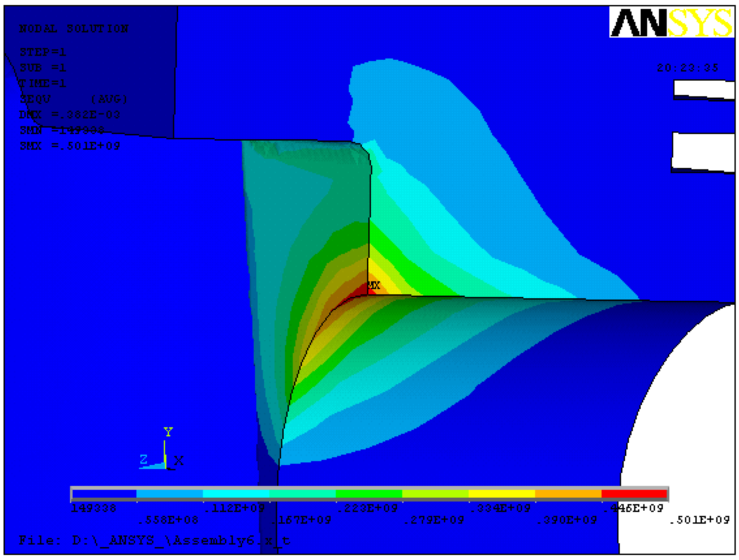


Figure 3.11. Gas forces stresses in Pa of steel piston.

On the next step there was investigated the steel thin-walled piston, Fig. 3.12. His temperature stresses are shown in the Fig. 3.13. Unallowable level over 350 MPa (for steel) is colored by gray enclosed by red. Simulation of the thermal expansion shows increasing of piston diameter on the fire surface in 0.5 mm.

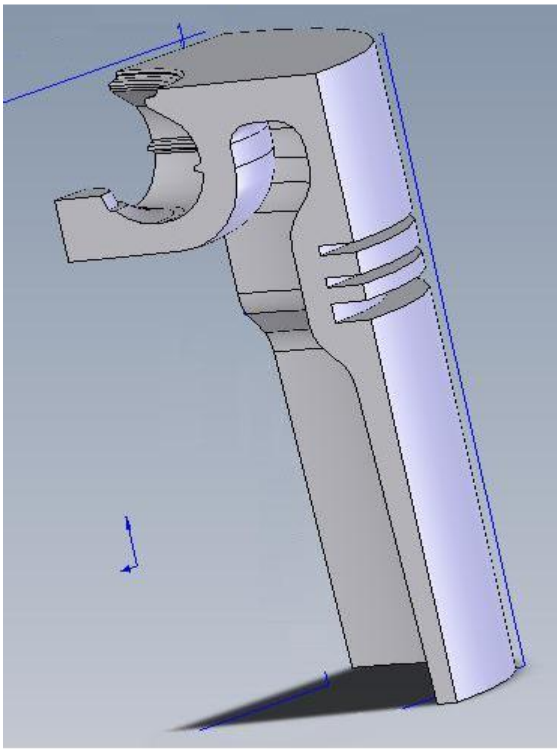


Figure 3.12. 3-D model of the steel thin-walled piston.

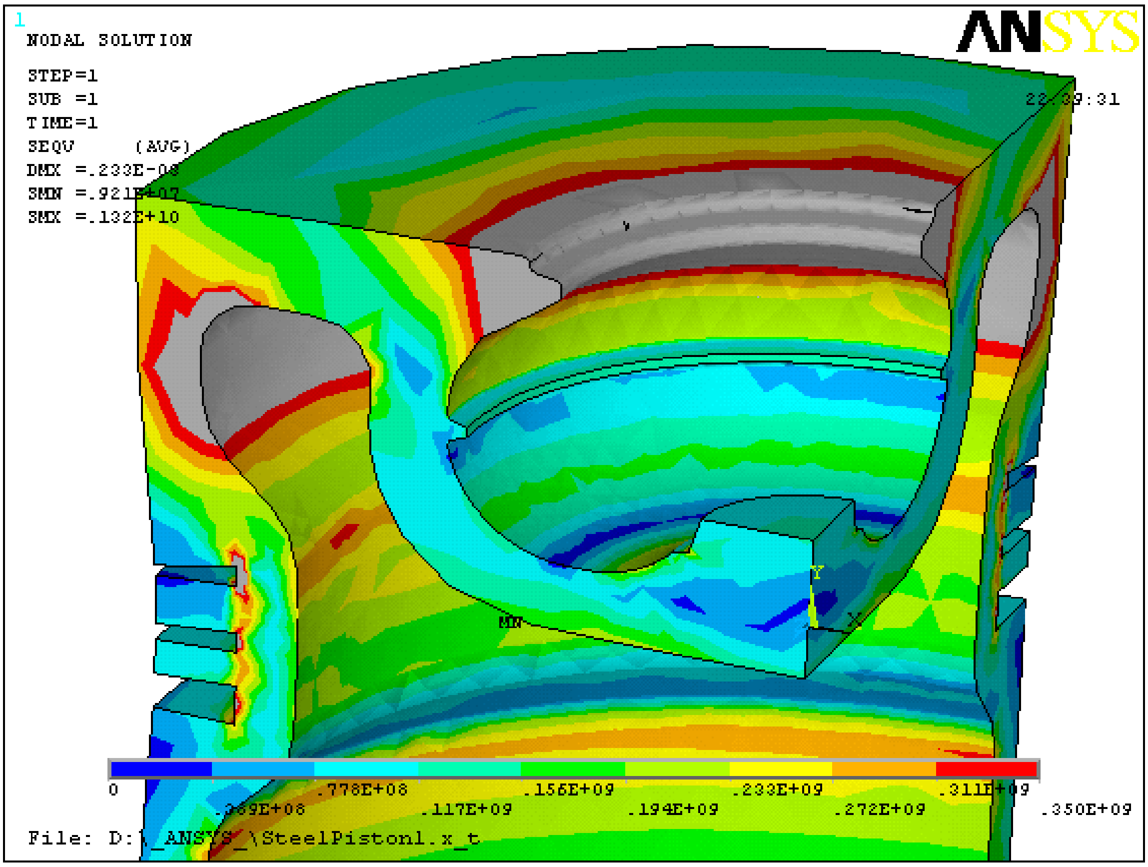
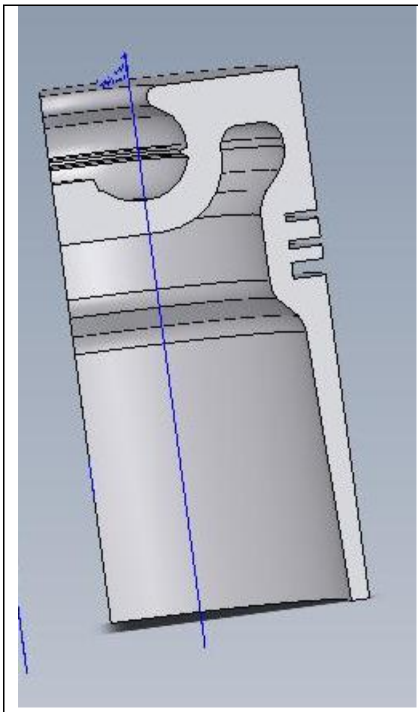


Figure 3.13. Temperature stresses in Pa of steel piston. Unallowable level over 400 MPa (for steel) is colored by gray enclosed by red.



An analysis of the stress map has shown the necessity to increase its rigidity. To do it the thickness of heated walls was increased as well as the piston bowl lip was done as radius R=1.5 mm, Fig. 3.14. The temperature map is presented in the Fig. 3.15. Unallowable level over 670 ^{0}C (for steel) is colored by gray enclosed by red.

Figure 3.14. 3-D model of the steel thick-walled piston.

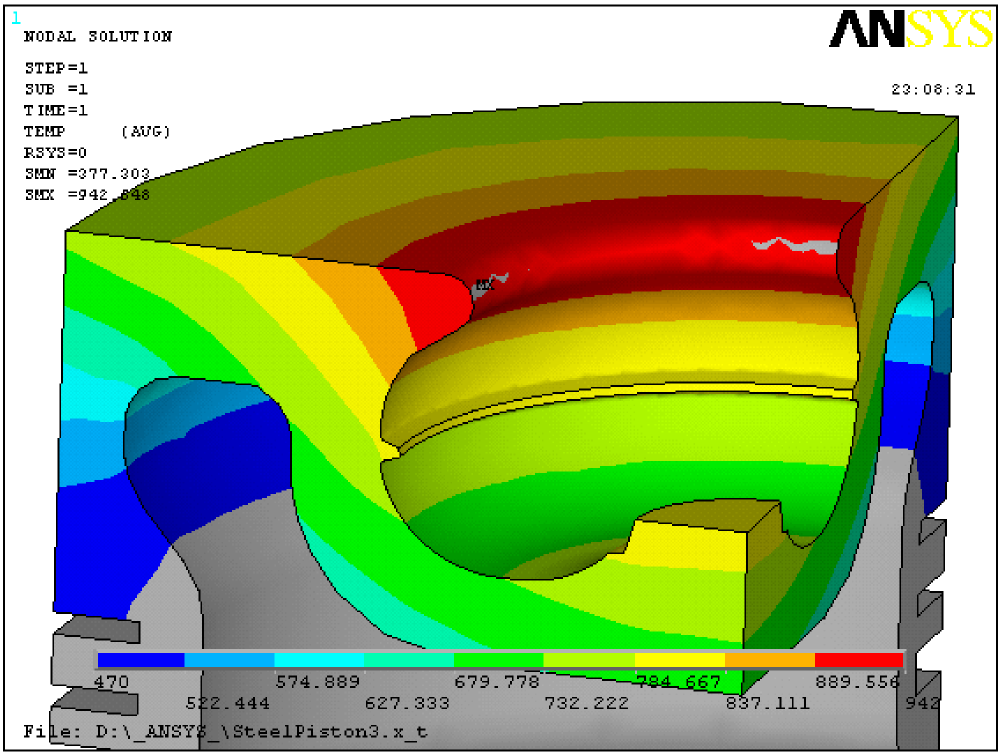


Figure 3.15. Temperature field in K of the steel piston combustion chamber. Unallowable level over 670 ^{0}C (for steel) is colored by gray enclosed by red.

Analysis of a temperature state of the piston shows necessity of general intensification of the piston.

To intensify the oil cooling the cast-in cooling gallery was done, Fig. 3.16. The heat transfer coefficient in the gallery was assumed as h=2500 W/m^2K. The obtained temperatures and temperature stresses are presented in the Fig. 3.17 – 3.18.

Figure 3.16. 3-D model of the steel thick-walled piston with cast-in cooling gallery.

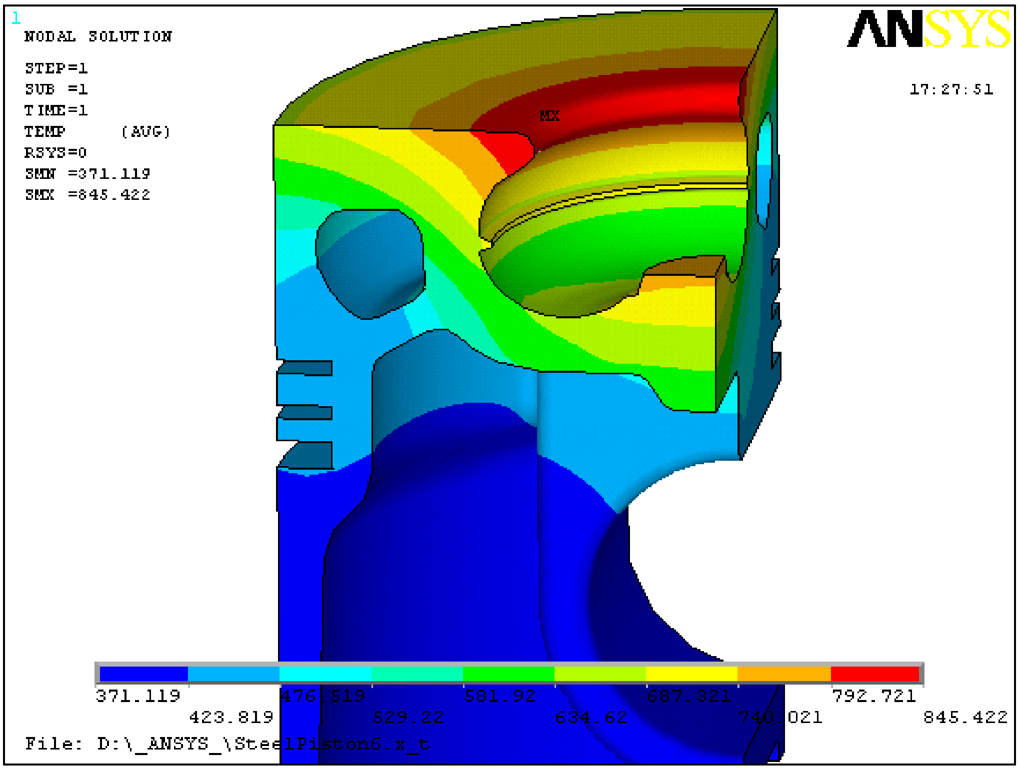


Figure 3.17. Temperature map in K of the steel thick-walled piston with cast-in cooling gallery.

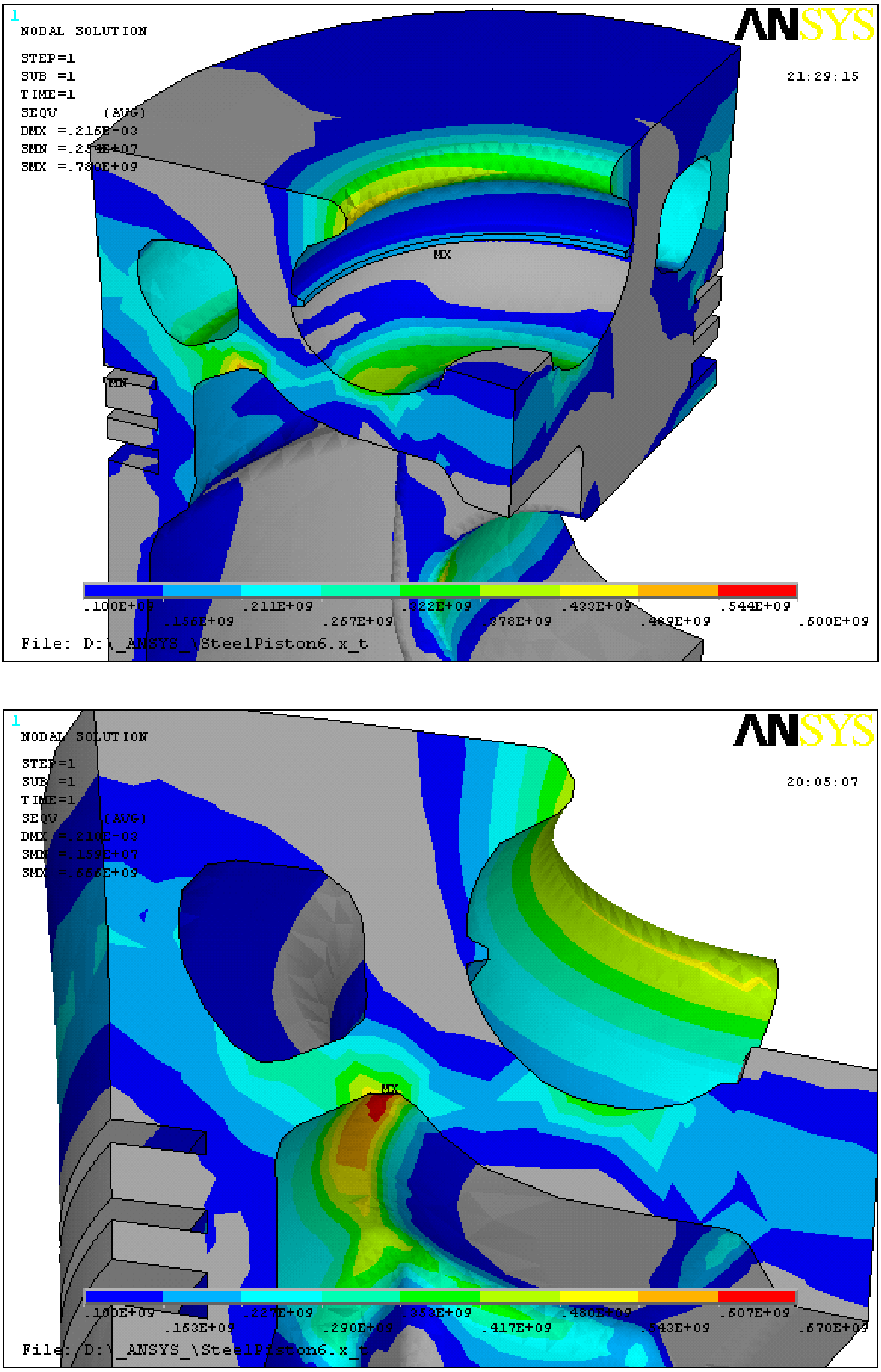
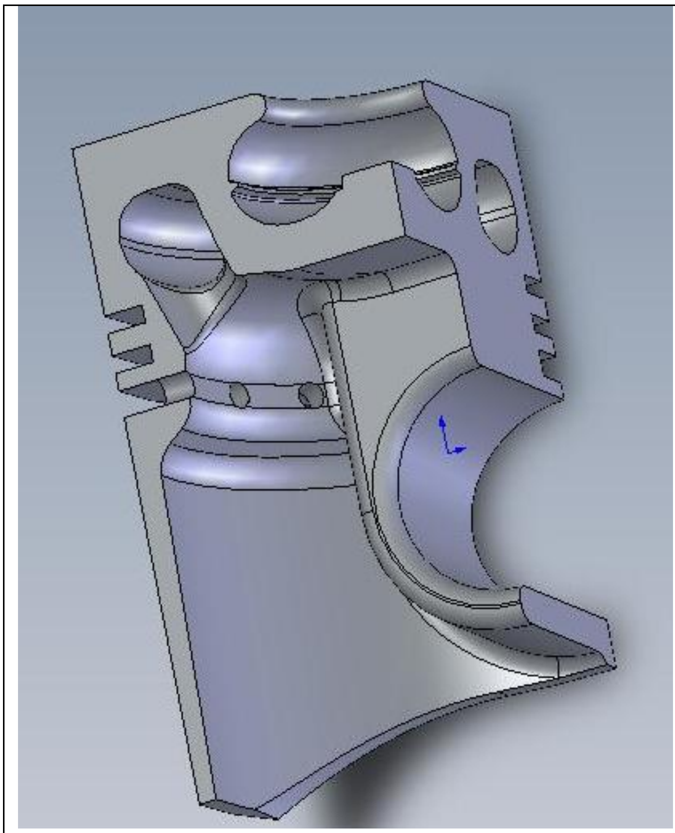


Figure 3.18. Critical region of the temperature stresses of the steel thick-walled piston with cast-in cooling gallery.

Analysis of data presented on the figure 3.18 shows the necessity to increase the radius in the region where maximum stresses appear.



The 3-D model of the piston with larger radius below the gallery is presented in the Fig. 3.19. The results of simulation are presented in the Fig. 3.20 – 3.21.

Figure 3.19. 3-D model of the steel thick-walled piston with cast-in cooling gallery and increased radius below gallery.

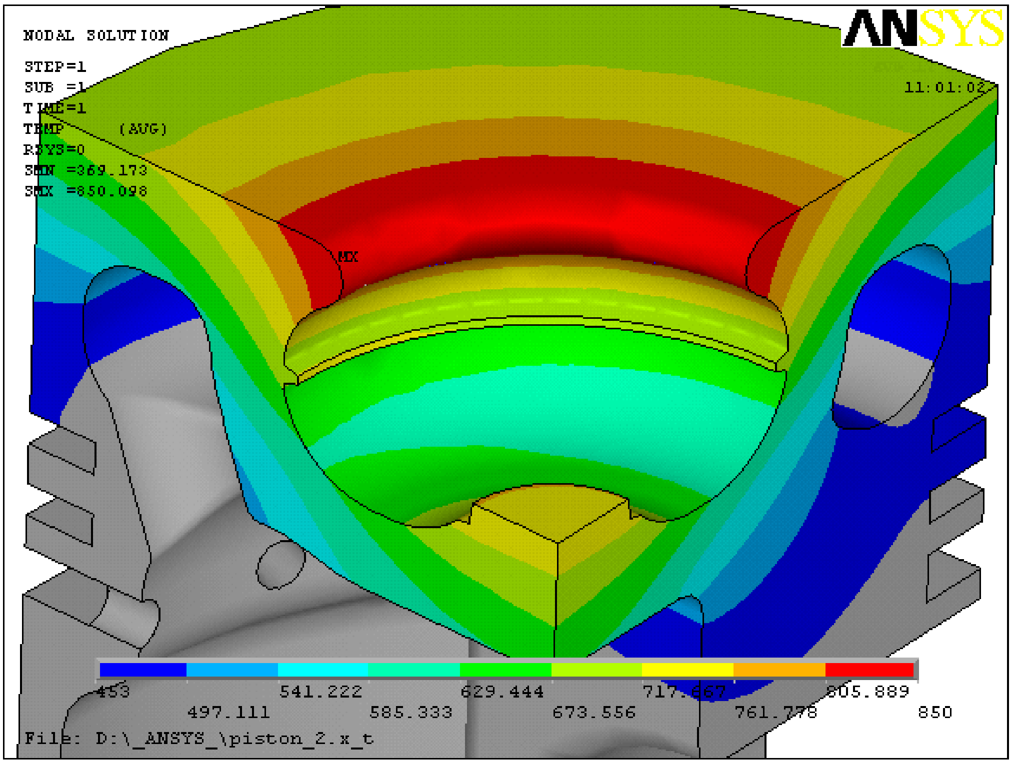


Figure 3.20. Temperature map in K of the steel thick-walled piston with cast-in cooling gallery and increased radius below gallery.

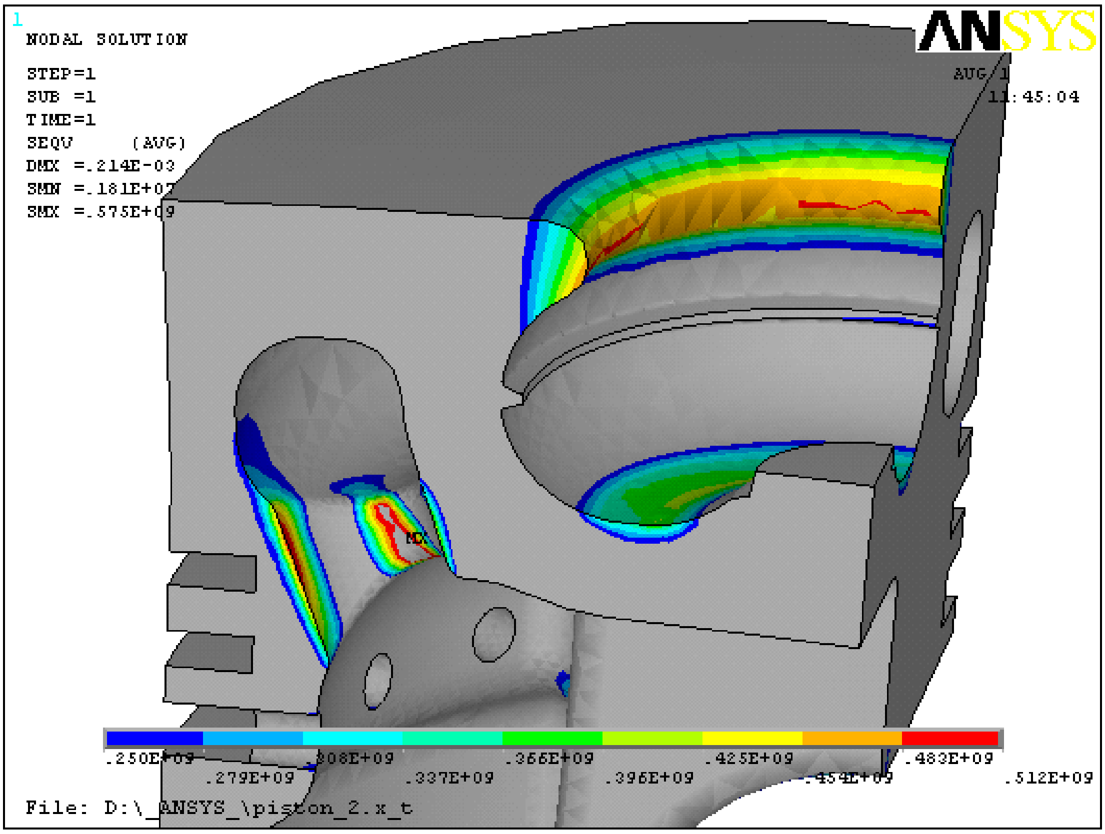


Figure 3.21. Critical region (gray enclosed by red) of the temperature stresses of the steel piston with cast-in cooling gallery and increased radius below gallery.

Analysis of the obtained data shows acceptable level of the temperatures, Fig. 3.20, (maximum temperature does not exceed 577 ^{0}C), but temperature stresses exceed 512 MPa in the hole intended to delivery a cooling oil to the gallery. To except the negative phenomenon the design of the oil delivery holes was changed, ones was shifted from plain of symmetrical, the radius of the bowl lip was increased up to 2.35 mm as well. The 3-D model of the modified piston is presented in the Fig. 3.22.

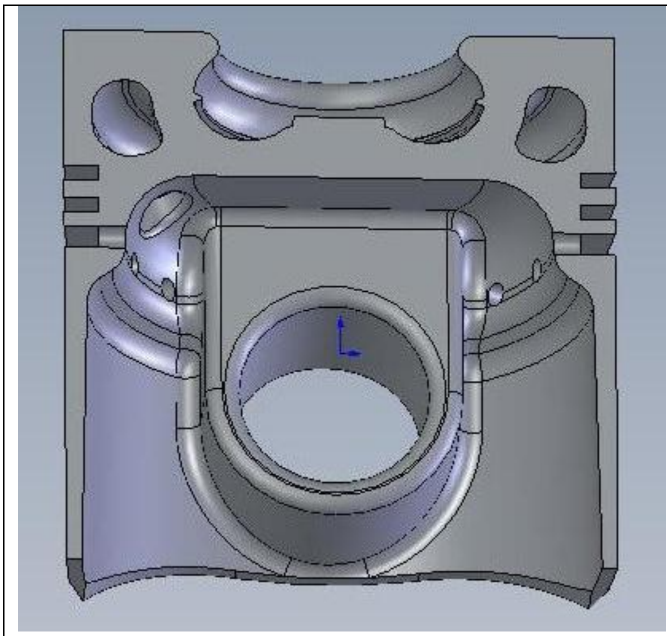


Figure 3.22. 3-D model of the modified steel piston

The obtained results are presented in the Fig. 3.23 – 3.24

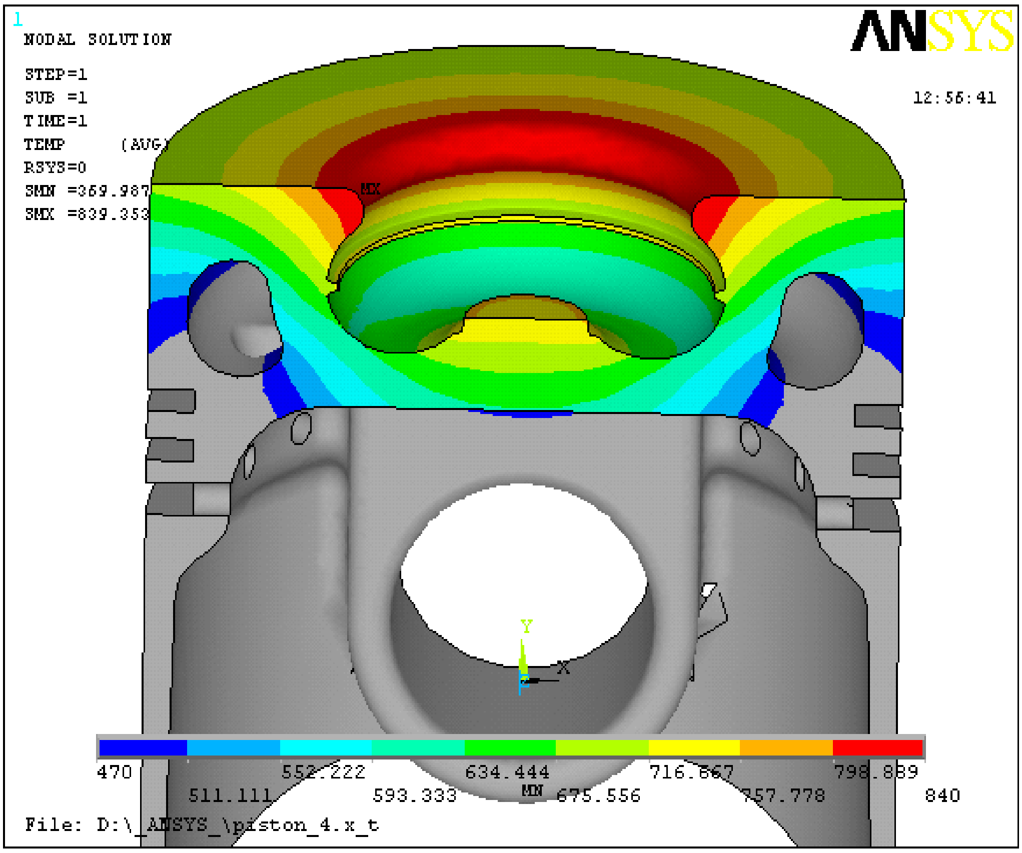


Figure 3.23. Temperature map in K of the steel piston with cast-in cooling gallery, increased radius below gallery and shifted oil delivery holes.

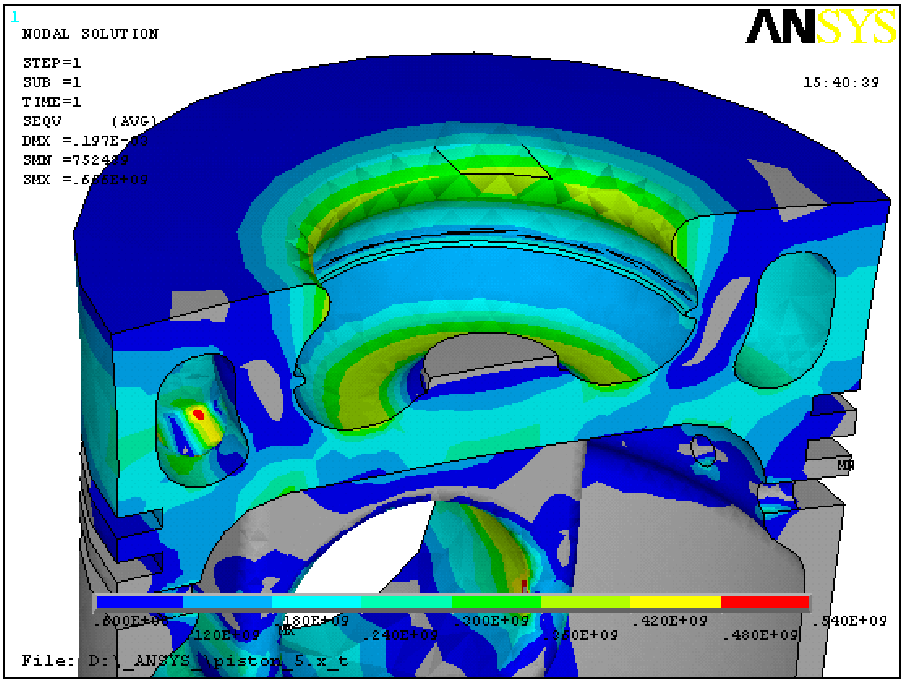


Figure 3.24. Stress map in Pa of the steel piston with cast-in cooling gallery, increased radius below gallery and shifted oil delivery holes.

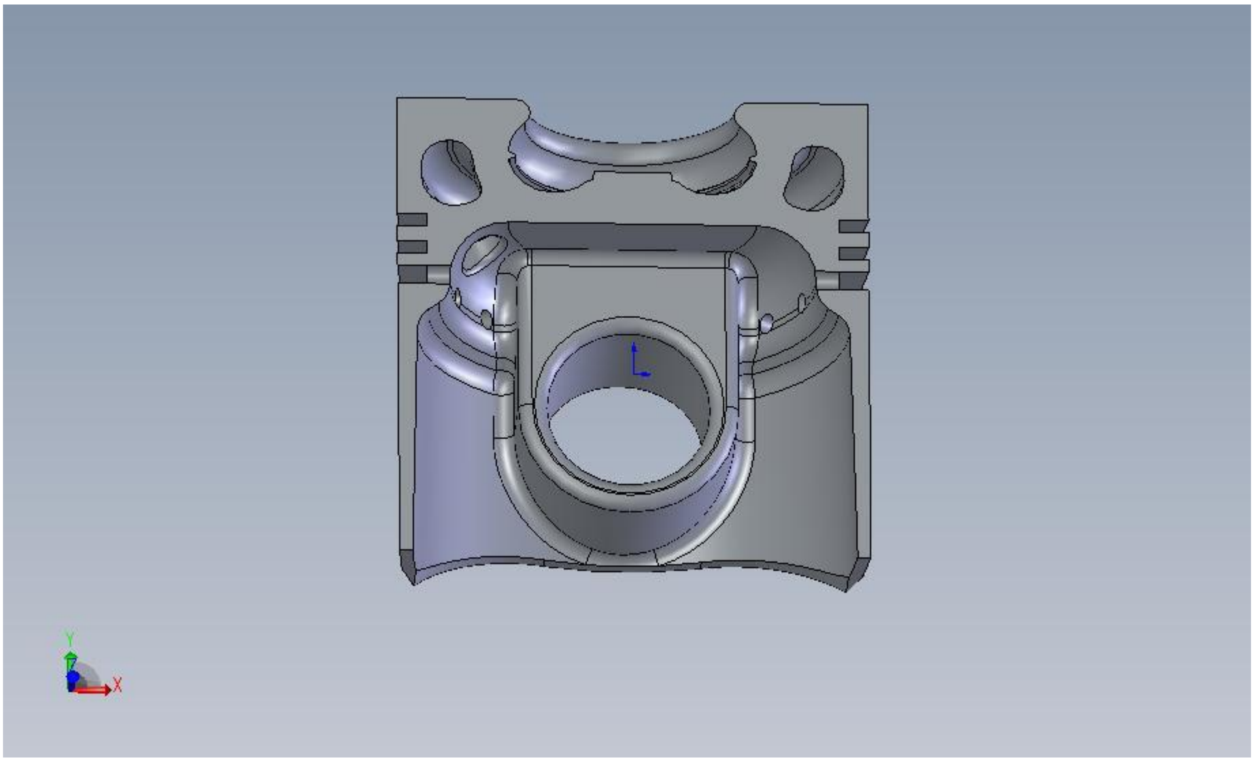
Last variant seems as laying near to acceptable: maximum temperature does not exceed 570 ^{0}C and maximum stress from heating exceeds 480 MPa only in a small region inside the oil delivery holes. For more detailed analysis it is necessary to repeat the last session of calculation with itemized properties of materials. The result drawing of the piston is presented in the Appendix.

ACKNOWLEDGMENTS

The author gratefully acknowledges contribution and support of academic staff at the BMSTU, in particular of Professor L. Grekhov and Ass. Prof. F. Barchenko. Finally, the authors would like to acknowledge that this research was ordered and supported by Aumet OY and Mr. T. Janhunen.

REFERENSES

1. Дизели. Справочник. Изд. 3-е, перераб. и доп. Под общей редакцией В.А.Ваншедта, Н.Н. Иванченко, Л.К. Коллерова. – Л.: Машиностроение, 1977. – 480 с.
2. http://ansys.com
3. Черкасский В.М. Насосы, вентиляторы, компрессоры: Учебник для теплоэнергетических специальностей вузов.- 2-е изд., перераб. и доп. - М.: Энергоатомиздат, 1984. - 416 с., ил.


Y
X