SUCCESSFUL DIESEL COLD START THROUGH PROPER PILOT INJECTION PARAMETERS SELECTION

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Introduction: The article contains description of the mathematic model of the cold start work process which can be used for injection parameter selection in electronically controlled fuel Common Rail Systems of diesel engines. Mathematic model is notable for taking into account compression leakage during cranking and dual-phase injection process at start mode. It is also shown review and analysis of computational research of pilot injection influence on work process parameters and dynamic of the crankshaft at the engine start mode at -10 ^{0}C without start aid. Mathematic model additionally allows calculate crankshaft acceleration time starting from cranking to low idle speed. The cold start test results with pilot injection application have been introduced with description and analysis. Engine test results, which are proved by simulation, showed real efficiency of pilot injection at cold start mode and allow reduce start time up to 3 times compared to engine start without pilot injection.

Technical paper

To provide reliable cold start of diesel engine thermodynamic parameters at the end of compress stroke should guarantee evaporation and ignition of fuel quantity to produce positive work bigger than engine friction torque work [2]. According to the Belarusian legislation reliable cold start at -10 ^{o}C should be guaranteed without cold start aid. To reach this legislation special methods and features are used [4]. The most reasonable way to provide better cold start is a pilot injection, which is useful during cranking and crankshaft acceleration up to low idle speed. Compression leakage has strong affect on cold start ability but research works which are announced in publish sources do not cover all the aspects of this process.

Effectiveness of activities providing reliable cold start may be improved by using work process computing model which allows calculate thermodynamics parameters of air charge at the end of compress stroke, simulate burning-out of start fuel quantity, define indicator diagram parameters and calculate time of crankshaft acceleration.

In common the first law of thermodynamics in finite-difference approximation for internal combustion engines can be of the form:

$$\Delta L + \Delta U + \Delta Q_w + i \cdot \Delta m_{lk} + \Delta Q_{dis} = \Delta Q \,, \tag{1}$$

where ΔL – work, performed at the calculated section;
ΔU – change of fresh air charge internal energy at the calculated section;
ΔQ_w – gases heat losses into combustion chamber walls at the calculated section;
ΔQ_{dis} – heat losses of gas molecules dissociation;
ΔQ – heat quantity transfer to working medium at the calculated section;
i – gases enthalpy at the calculated section;
Δm_{lk} – compression leakage at the calculated section.

As a rule, last two summands are not taken into consideration in work process simulation for engine speed bigger than low idle. But in compression simulation for engine cranking it is needed to take into account compression leakage through twains like liner-piston and valve-seat.

Solving equation relative to pressure at the end of calculated section taking into account calculation of internal energy change we get the following relation:

$$p_i = \frac{2\cdot\left(\Delta Q - \Delta Q_w \ - i\cdot\Delta m_{lk}\right) + p_{i-1}\cdot\left(\left(2\cdot\frac{C_V}{R}+1\right)\cdot V_{i-1} - V_i\right)}{\left(2\cdot\frac{C_V}{R}+1\right)\cdot V_i - V_{i-1}}, \qquad (2)$$

where p_i V_i – pressure and volume of fresh air charge at the end of calculated section;

p_{i-1} V_{i-1} – pressure and volume of fresh air charge at the begin of calculated section;

C_v – working medium heat capacity at the constant volume;

R – absolute gas constant (8.314 kJ/(kmole·K)).

Heat quantity ΔQ_w, transferred by fresh charge into walls can be calculated with the help of Newton-Ryman equation.

Fresh air quantity lost through leakages calculated with the help of equations which are mentioned in the work [2]. To calculate the temperature of fresh charge at the end of calculated section the characteristic equation of Mendeleev-Klapeiron is used. Making work process simulation at cold start mode characteristics of fuel burning-out were calculated with the help of known methodic [1].

Equations are mentioned above are used in programming module which allows to calculate parameters of fresh charge during cranking and to define parameters of work process during crankshaft acceleration.

With the help of programming module influence assessment of pilot injection quantity on work process parameters was done. Simulation was performed for different injection timing, and engine speeds with a glance of compression leakage.

Making calculation research pilot injection quantity varied from 1 to 10 mm^3 at the same time length of pilot injection was equal to 1^o of crankshaft rotation and constant. The minimum possible stable injection quantity in Heavy Duty CRS system is equal usually to 2 mm^3 [3] but can be decreased in the future.
Work process simulation with another length of pilot injection is not reasonable du to decrease of fuel outflow average speed and as a result increase of fuel droplets average size which is not good for mixing [3].
Start of injection should be correlated with moment in which the temperature of fresh air charge is enough for fuel evaporation. But at the same time injection timing should not be too early so ignition would not be very early providing high level of maximum combustion pressure. If timing is too late bigger part of air charge heat would be transferred in the walls of combustion chamber and left heat energy would be not enough for fuel evaporation and ignition. Simulation research of timing reasonable value was performed between 20^o before top dead center (BTDC) and top dead center (TDC).

Pause between pilot and main injections varied from 3^o to 10^o. Fewer pauses are not reasonable as ignition would be very similar to single-phase injection.

Expansion of this pause can lead to low effectiveness of air charge temperature increase provided by pilot injection due to heat lost and end of burning. Late timing and burning of main injection after TDC make indicator parameters worse and this has negative influence on acceleration characteristic of the diesel.

Work process simulation was done for 6-cylinder in-line diesel with dimensionality 11.5×14; common start injection quantity was 130 mm^3. Main injection length was 5^o of crankshaft rotation. This fuel delivery with the same speed of needle nozzle opening provides required level of injection pressure. Maximum pressure and temperature were chosen as evaluating parameters of work process.

Influence of pilot injection quantity and injection timing on work process parameters

Simulation results show that pilot injection quantity increase leads to growth of the maximum temperature and pressure. Absolute growth value of the maximum pressure at increase of pilot injection quantity from 1 to 10 mm^3 is about 1.54 MPa (35%), and maximum temperature is about 250^o (34%). Maximum pressure and temperature achieving for the timing is equal to 20^o BTDC. Changing timing from 14^o to 6^o BTDC maximum pressure and temperature are slowly decreasing in dependency from injection quantity.

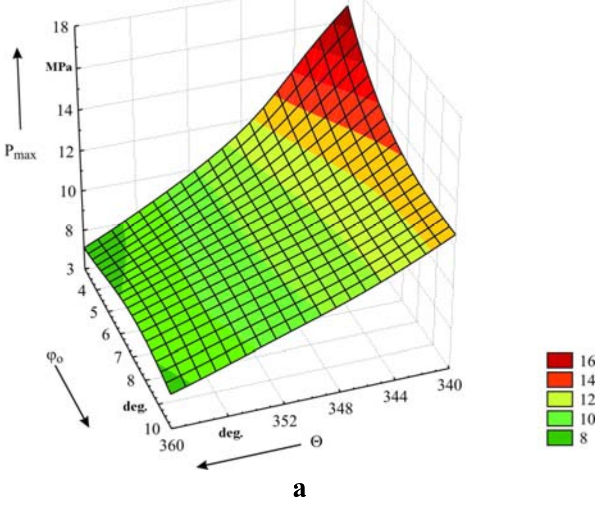
Disadvantage of early injection is high “rigidity” burning process; maximum speed of pressure increase is higher than 0.81 MPa/degree at pilot injection quantity equal to 10 mm^3. For timing 6^o BTDC speed of pressure increase is equal to 0.74 MPa/degree.

Influence of pilot injection quantity and crankshaft speed on work process parameters

Intensity of maximum cycle pressure change in dependency of injection quantity and crankshaft speed is more or less the same. The difference is in the pattern of change: at injection quantity increase this parameter is changing almost linearly, but at engine speed n increase – irrationally.
With injection quantity increase starting from 5 mm^3, dependency of cycle maximum temperature becomes not so noticeable. At pilot injection quantity bigger than 6 mm^3 maximum cycle temperature exceeds 800 K for every engine speed within simulated range. Maximum pressure for engine speed simulated range at injection 6 mm^3 becomes greater on 1.8 MPa (~60%), at the same time the temperature is increased only on 50^o (~6.5%). Pressure growth with increase of pilot injection quantity from 6 to 10 mm^3 is more or less the same for every engine speed. For n=50 min^{-1} maximum pressure increase is equal to 0.69 MPa, but for n=300 мин$^{-1}$ is equal to 0.72 MPa.
Obviously, that the most comfortable conditions for main injection ignition are reached with pilot injection quantity equal to 10 mm^3.

Influence of the injection timing and injection pause on work process parameters

Indicator parameters of the diesel work process are calculated for different values of pauses between injections and injection timings are shown on the figure 1. Simulation was performed at engine speed equal to 200 min^{-1} and effective leakage area section μ_f equal to 1.5 mm^2, pilot injection quantity equal to 10 mm^3, and common injection quantity equal to 130 mm^3.



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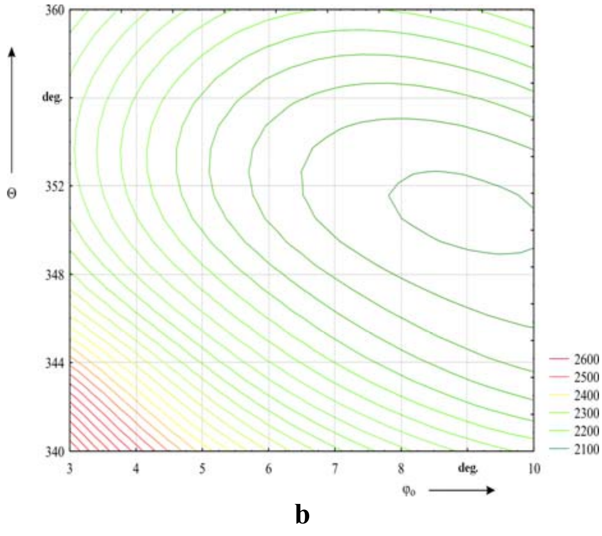

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Figure 1: Maximum pressure:
a – in MPa and temperature;

b – in ^{o}K dependencies subject to injection timing and length of pause between injections

The highest levels of maximum pressure and temperature are reached with early timing and short pause between pilot and main injections. In this case almost all quantity is injected before TDC. Due to low temperature of fresh charge (585 K) ignition delay of pilot injection quantity is quite long (~7 degrees), main part of the fuel is injected before pilot injection ignition. In this case burning of the fuel is equal to single-phase injection. At the pause length 3 degrees and injection timing equal to 20^{o} BTDC maximum pressure exceeds 17 MPa, maximum temperature is more than 2600 K, and maximum pressure increase speed is about ~2.5 MPa/degree.

Pause length decrease promote to maximum pressure and temperature decrease. Absolute values of these parameters are greater than 2200 K and 12 MPa accordingly.

At injection timing close to TDC maximum pressure become less great than 8 MPa and maximum temperature remains quite high is about 2200 K.

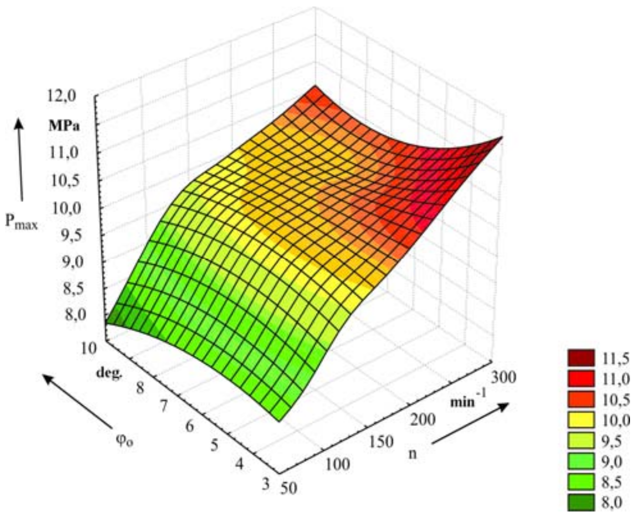
Work process of diesel engine cold start at different engine speeds and pauses length between injections φ_o

Results of work process simulation are shown on the figure 2. Calculation was made for timing 10^{o} BTDC. Effective leakage area section μ_f was equal to 1.5 mm^2.

The strongest influence on indicator parameters has a change of engine speed. High values of maximum pressure at high engine speeds are caused by lower level of heat transfer and low level of compression leakage. At engine speeds lower than 100min^{-1} at any length of the pause maximum pressure and temperature don't exceed 9 MPa и 2100 K.

Twice bigger value of engine speed doesn't lead to big increase of evaluated parameters, maximum pressure becomes a little bigger than 10 MPa, and temperature slightly bigger 2100 K, at the same time maximum speed of pressure increase is less than 2 MPa/degree.

With n increase influence of pause length on indicator parameters becomes stronger and at φ_o increase maximum pressure is decreasing on 1.2 MPa, and temperature is decreasing on 70^{o}.



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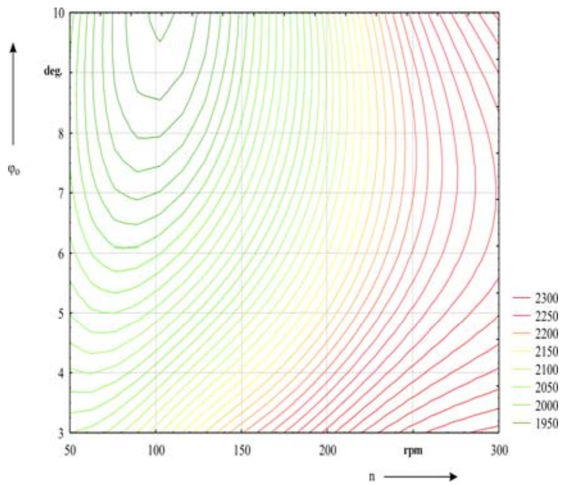

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Figure 2:Maximum pressure:
a – in MPa and temperature;
b – in ^{o}K dependencies subject to cranking speed and length of pause between injections

Influence of engine speed and injection timing on work process parameters at start mode

Results of work process simulation are shown on the figure 3.

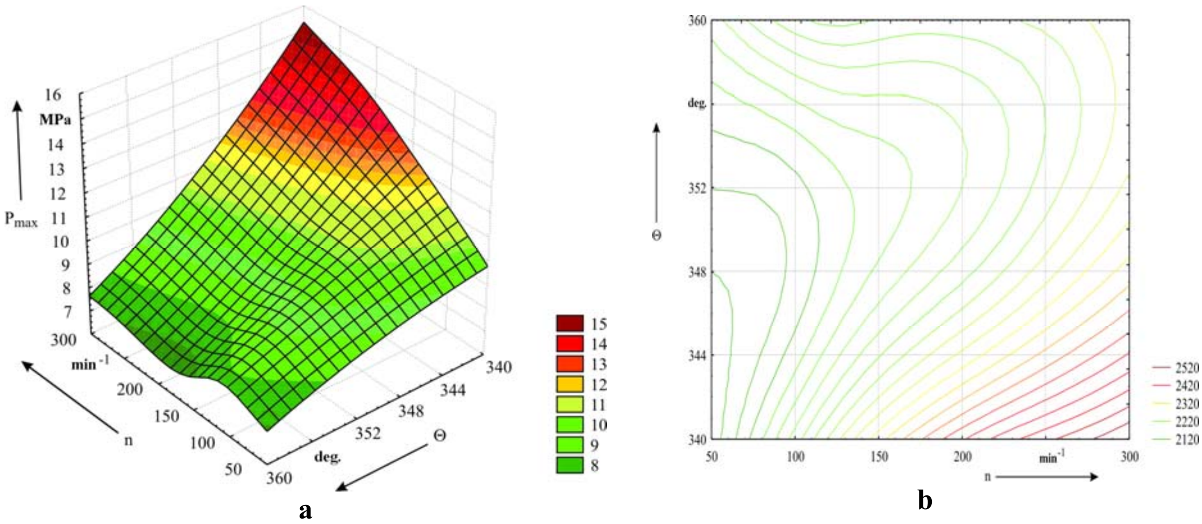

Figure 3: Maximum pressure:
a – in MPa and temperature;
b – in ^{o}K dependencies subject to cranking speed and injection timing

Injection pause was 5^{o} and μ_f was equal to 1.5 mm^2. The biggest values of maximum pressure and temperature were noted at high engine speed and early injection timing. Dependency of maximum pressure and temperature becomes weaker with decreasing of engine speed. For example at n=50 min^{-1} these parameters with injection timing 20^{o} BTDC are bigger accordingly on ~3.3 Mpa (49%) and 110^{o} (8%), than at timing 0^{o} BTDC. At the same time difference between thermodynamic parameters for n=300 min^{-1} and injection timing 20^{o} and 0^{o} BTDC is 7.3 Mpa (almost two times bigger) and 165^{o} (7.3%). With late injection timing 2^{o} and 0^{o} BTDC maximum pressure stays nearly constant for whole range of engine speed.

These dependencies for different engines speeds allow choosing combination of injection timing, pilot injection quantity and length of the pause between injections to provide needed crankshaft dynamic during acceleration and allowable level of mechanic load. Analysis results shows that the most effective cold start work process will be provided at pilot injection quantity equal to 8…10 mm^3, injection timing equal to 15…20^{o} BTDC, and length of injection pause equal to 6…8^{o}.

Simulation of crankshaft acceleration at cold start mode

Work process analysis at cold start mode provides possibility to define reasonable parameters of fuel injection only for the first cycle of the fuel ignition at current engine speed, but there is no possibility to evaluate engine start from the point of objective operational conditions. Start time which is consist of cranking time and crankshaft acceleration time [5], is the objective result of chosen fuel injection parameters, providing required work process parameters at cranking and acceleration.

Crankshaft movement at start mode determinates by total engine torque $\sum M_{ic}$, engine friction torque M_{frc} and electric starter torque M_{st}. In this case equation of the crankshaft movement can be the form of:

$$J \cdot \frac{d\omega}{dt} = M_{st} + \sum M_{ic} - M_{frc}, \qquad (3)$$

where J – total moment of inertia of moving parts, modified to crankshaft axle.

Diagram of engine acceleration is a result of equation (1) solution, which allows evaluate efficiency of work parameters influence on acceleration time.

Solving differential equation (1) associated with difficulties caused by the following: torques which are right part of the equation, are functions of crankshaft position angle and engine speed. To reduce the number of variables change of time based variables to crankshaft position angle based variables was performed. After making this and changing angular speed ω on engine speed n dependency (1) is of the form:

$$\frac{dn}{d\varphi} = \frac{900}{\pi^2 \cdot J}\left(M_{st} + \sum M_{ic} - M_{frc}\right), \tag{4}$$

Array of engine torques is divided on intervals. Number of intervals is determined by number of cylinders. After that torque values of each interval are summarized to get value of total engine torque $\sum M_{iц}$ for current crankshaft position. To get engine friction torque empirical dependences subject to oil viscosity were used. Electric starter torque is determined by speed ability characteristic and drive parameters.

Salvation of differential equation (4) was done with the help of numerical methods. Simulation of crankshaft acceleration is making based on the work process calculation results. To get forces from gas pressure indicator diagram is used. Values of mass and moment of inertia are taken from engine technical profile. Value of oil body is taken from viscosity-temperature characteristic for chosen oil sort.

Dependences are mentioned above were used for program, which allows calculate crankshaft acceleration time at engine start mode.

Crankshaft acceleration characteristics at double-phase fuel injection

Calculation research was done for 6-cylinder in-line diesel with dimensionality 11.5×14 at the level of ambient temperature equal to -10 °C. Cranking speed provided by electric starter was equal to 145 min^{-1}. Due to engine speed change during acceleration another parameter ranges were used for simulation: injection timing Θ varied from 20^o to 36^o BTDC, injections pause θ varied from 6^o to 14^o, injection quantity varied from 120 to 150 mm^3.
Figure 4 shows acceleration characteristic subject to injection quantity. Calculations were performed for injection timing Θ equal 20^o BTDC and injection pause θ legth equal to 10^o. Increase of injection quantity decreases number of cycle to reach low idle minimum sped on 3, what is equal to 0.08 s. At the same injection quantity and timing acceleration is faster with double-phase injection on 1 cycle.

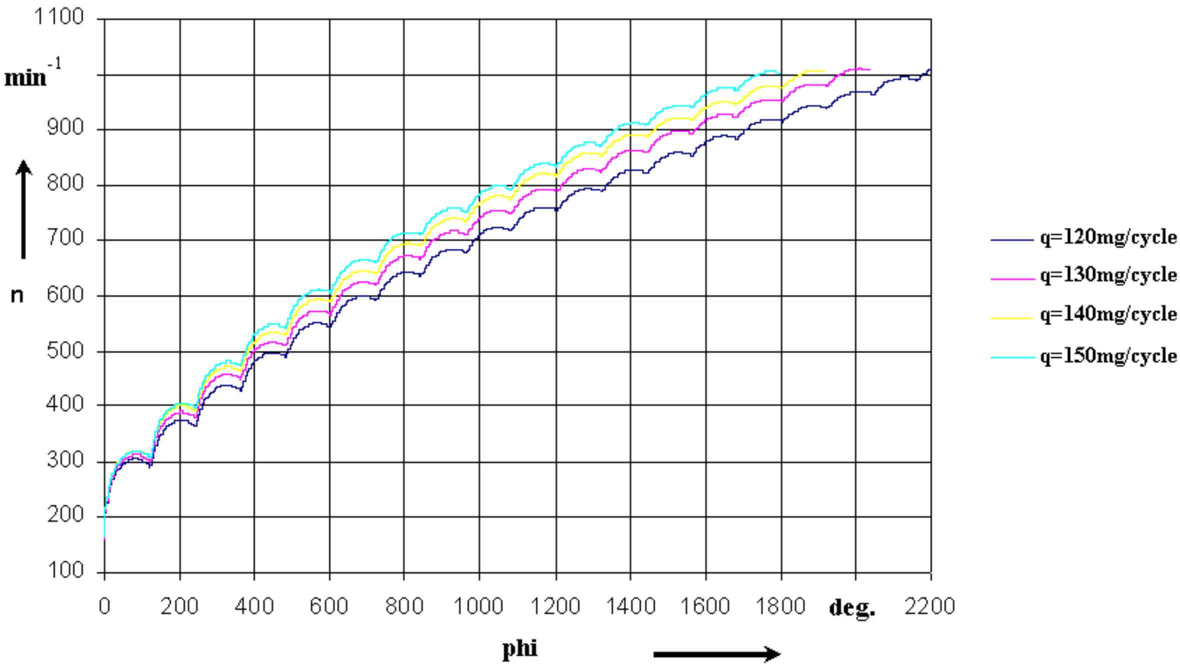

Figure 4: crankshaft acceleration characteristics with double-phase injection subject to injection quantity

Analysis of acceleration characteristics for different injection timing shows that early injection leads to high acceleration speed: number of cycles to achieve 1000 min^{-1} decreases on 7 (840 degrees of crankshaft rotation), time interval decreases on 0.2 s. Early pilot injection creates conditions for evaporation and ignition of main injection quantity, what improves efficiency of work process and leads to rise of engine torque. Simulation was performed at injection quantity equal to 130 mm^3 and length of the injection pause θ is equal to 10^o of crankshaft rotation.

Influence of the length between injections on acceleration characteristics is not so efficient. Simulation was done at injection timing quantity equal to 130 mm^3 and injection timing Θ equal to 20^o BTDC. Difference in the number of cycles to accelerate crankshaft wasn't bigger than 3.

Higher crankshaft acceleration was reached at double-phase injection with injection timing Θ equal to 36^o BTDC, injection quantity 130 mm^3 and length of the pause equal to 10^o (14 cycles). At single-phase injection the highest acceleration was reached at injection quantity equal to 150 mm^3 and injection timing equal to 20^o BTDC (15 cycles). Time difference is very low and less big than 0.02 s.

Cold start test results at dual-phase injection

Simulation research shows that indicated engine horsepower at start mode and thus acceleration characteristics depend in general from fuel injection parameters. Results of simulation were compared to experimental test results conducted at Minsk Motor Plant cold chamber. Tests were performed at -10 ^oC. As evaluation parameters were chosen time of engine start t_{st} and time to the first flame t_{fl}.
Varied parameters were injection timing, length of the injection pause and pilot injection quantity. Cold start parameters were controlled in real-time mode (figure 5).

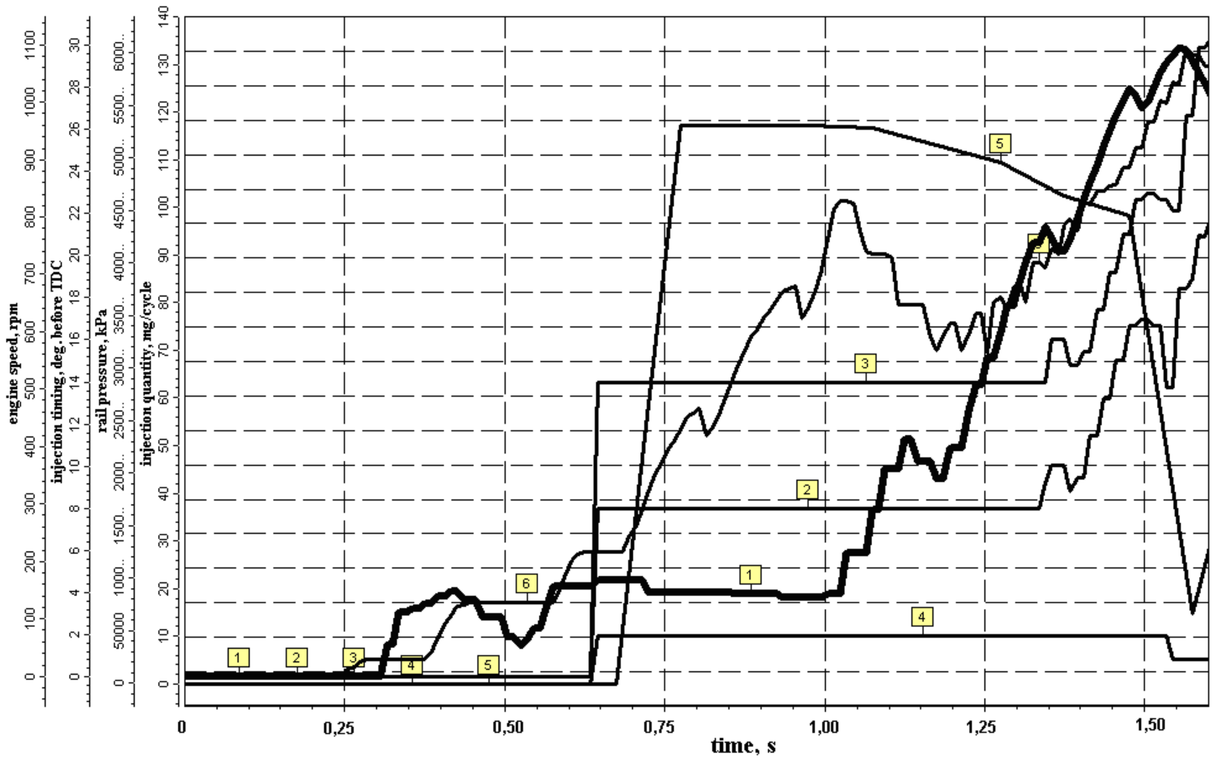

Figure 5: D-263.1E3 cold start diagram:
1 – engine speed, min^{-1}; **2** – injection timing of main injection, deg. BTDC;
3 – pilot injection timing, deg. BTDC; **4** – pilot injection quantity, mg/cycle;
5 – main injection quantity, mg/cycle; **6** – rail pressure, kPa.

Search of reasonable parameters of the fuel injection was made by step-by-step approach. At the first stage main injection parameters were chosen (injection timing and pressure without pilot injection). At the second stage subject to chosen parameters of main injection pilot injection quantity g_p and timing were choosing.

Making the first stage of this research main injection timing was varied between 3^o and 12^o. Minimum start time was reached at Θ equal to 9^o BTDC.

Probably at $\Theta=9^o$ BTDC air charge energy is used more efficiently. At early injection (more than 9^o BTDC) temperature of fresh air charge is lower and considerable fuel quantity at very short injection (about 2…3^o) concentrated near the walls of the combustion chamber and evaporation in this case is negligible.

At late injection (less than 9^o BTDC), fuel is injected, when the temperature maximum have been reached and evaporation process goes at decreasing temperature, which lead to vapor quantity decrease. At the same time heat loss leads to decrease of air charge energy which is not enough for ignition.

Thus, better cold start results were reached at $\Theta=9^o$ BTDC and P_{rail} = 25 MPa. At the second stage these parameters were kept constant. Pilot injection quantity g_p was varied from 5 to 10 mg/cycle and injection pause φ_o was varied from 3^o to 12^o.

Use of pilot injection improves start characteristics of diesel engine: start time was decreased in more than 3 times, and t_{fl} was decreased in more than 2 times.

The best performance of cold start was reached at g_p = 10 mm^3 and φ_o= 6^o before main injection. With the same value φ_o start time is less and at g_p = 5 mm^3. Decreasing of φ_o leads to increase of start time. Increasing of φ_o up to 9^o and 12^o also lead to start time increase on 0.5…0.6 s.

Conclusions

1. Developed methodic of diesel work process simulation at cold start mode, which allows define reasonable fuel injection parameters.

2. Obtained dependencies, allowing evaluate influence of pilot injection quantity on thermodynamics parameters of the work process at different engine speed and injection timing. At pilot injection quantity more than 7 mm^3 heat losses and compression leakage are fully compensated for engine speed more than 100 min^{-1}, and effective leakage area section not more than 1.5 mm^2.

3. To get reliable cold start of investigated type of diesel engine at ambient temperature -10 ^{o}C without start aid recommended using of dual-phase injection. Pilot injection quantity 8…10 mm^3 should be injected into combustion chamber 14^o …17^o BTDC, and main injection quantity equal to 120 mm^3 should be injected later than pilot on 6^o …8^o.

4. Developed mathematic model of diesel engine acceleration, which is notable for taking into account features of the work process, change of engine friction torque and electric starter torque at crankshaft acceleration, allowing obtain diesel acceleration characteristic at different start conditions and parameters of fuel injection.

5. Conducted simulation research of influences fuel injection parameters on diesel start characteristic. Established that dual-phase injection of 130 mm^3 with optimum injection timing provides engine acceleration up to 1000 min^{-1} faster than acceleration at single-phase injection of 150 mm^3 with optimum injection timing.

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