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COMPARATIVE ANALYSIS OF NATURAL GAS ENGINE PARAMETERS WITH QUALITY AND QUANTITY CONTROL

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Parameters of natural gas engines were calculated with the aim to determine the optimal way of their working process organization. Analysis of calculations results demonstrated that quality power level control ensured the improvement of parameters of investigated engines. Calculations showed that compared with the diesel engine, the gas engine with quantity power level control, internal mixture formation and glow plug ignition of the gas-air mixture ensured the decrease of CO_2 emissions by 26.8%, and the natural gas engine with quality power level control, external mixture formation and gas-air mixture ignition by a small pilot portion of fine atomized diesel fuel supplied by a Common Rail fuel system – by 25.5%. Therefore, one can choose one or another method of diesel engine conversion for operation on gas fuel considering available technical opportunities and with minimal expenses.

Diesel engine, gas engine, quality power control, quantity power control, dioxide carbon emissions calculation

Introduction

The paper is dedicated to comparative analysis of working processes of a diesel engine and four versions of natural gas engines to estimate their operation parameters and, first of all, carbon dioxide (CO_2) emissions which impacts of "greenhouse" effect. Four different ways of working processes of gas engines are analyzed in detail, in particular, quantity and quality methods of power level control and gas-air mixture inflammation.

The goal of the research

The goal was to choose the experimental data and computer modelling methods for the most suitable way of the organization of the working process of a natural gas powered engine which ensures the highest reduction of carbon dioxide emissions using 13-stage cycle according to the Rule ECE R49.

Analysis of the working process organization in natural gas engines

There may be many methods of the organization of the working process in natural gas powered engines. We shall analyze briefly few methods of conversion of diesel engines to operate on natural gas (Shatrov *et al*. 2013). These versions of gas engines will be later used for calculating their operation parameters.

1. A natural gas engine designed on the base of a diesel engine having spark ignition and quantity power level control. This may be generally the stoichiometric gas engine or the lean mixture gas engine. Operation at the stoichiometric gas-air mixture results in considerable drop of fuel efficiency and hence – increase of CO_2 emissions, thermal strain of the engine compared with the lean mixture gas engine. The lean mixture gas engine does not have these limitations and has one more advantage – its nitrogen oxides emissions level is much lower than that of the stoichiometric gas engine which makes it possible to avoid the use of the reduction catalyzer. Therefore, we used the lean mixture gas engine for our calculations.

2. A natural gas engine designed on the base of the diesel engine having spark plug or glow plug ignition and quality power level control. In this case, the problem of ignition of the gas-air mixture arises because, in contrast to diesel fuel, which has the self-ignition temperature about 350^{o}C, the self-ignition temperature of natural gas is about 700^{o}C. Therefore, to ignite the gas-air mixture, one has to use special heavy duty spark plugs or glow plugs and find experimentally the proper location place of the plug in relation to the gas injector sprays. Another approach is mounting the gas injectors in the intake system and using a pilot portion of diesel fuel for the inflammation of the gas-air mixture. One can use a traditional diesel fuel injection system and inject 15-25% of pilot diesel fuel portion. But the best solution based on the latest developments in diesel fuel supply systems is using the Common Rail system for injection of a pilot portion of diesel fuel. In this case, due to much higher injection pressure and computer control, it is possible to attain a fine atomization of the diesel fuel which makes it possible to decrease the portion of the diesel fuel to 3-5%. Though to realize this method, one has to protect from overheating the injector nozzles because their cooling by fuel is poor due to small portions of fuel injected.

Objects of investigation

1. The base diesel engine (KAMAZ 74051-320) V-8 with piston diameter D=120 mm and piston stroke S=120 mm, compression ration ε=17.0:1.
2. An engine designed on the base of the KAMAZ diesel engine, supplied with natural gas, having spark ignition and quantity power level control.
3. An engine designed on the base of the KAMAZ diesel engine, supplied with natural gas, with glow plug ignition and quality power level control.
4. A gas diesel engine designed on the base of the KAMAZ diesel engine with quality power level control and supply of 15 mg of diesel fuel pilot portion injected by a traditional direct injection fuel supply system.
5. A gas diesel engine designed on the base of the KAMAZ diesel engine, with quality power level control and supply of 3 mg of pilot portion of a fine atomized diesel fuel injected by a Common Rail fuel supply system with electro-hydraulic injectors.

Results of calculations of two natural gas powered engines with respect to load characteristics

Parameters of natural gas engines with quality and quantity power level control were calculated by the model of joint operation of a gas engine with a turbocharger (Khatchiyan *et al*, 2010) at two engine operation modes: maximum power (n=2200 rpm) and maximum torque (n=1400 rpm).

Figure 1 shows the calculated characteristics of two natural gas engines having quality and quantity power level control versus mean effective pressure.

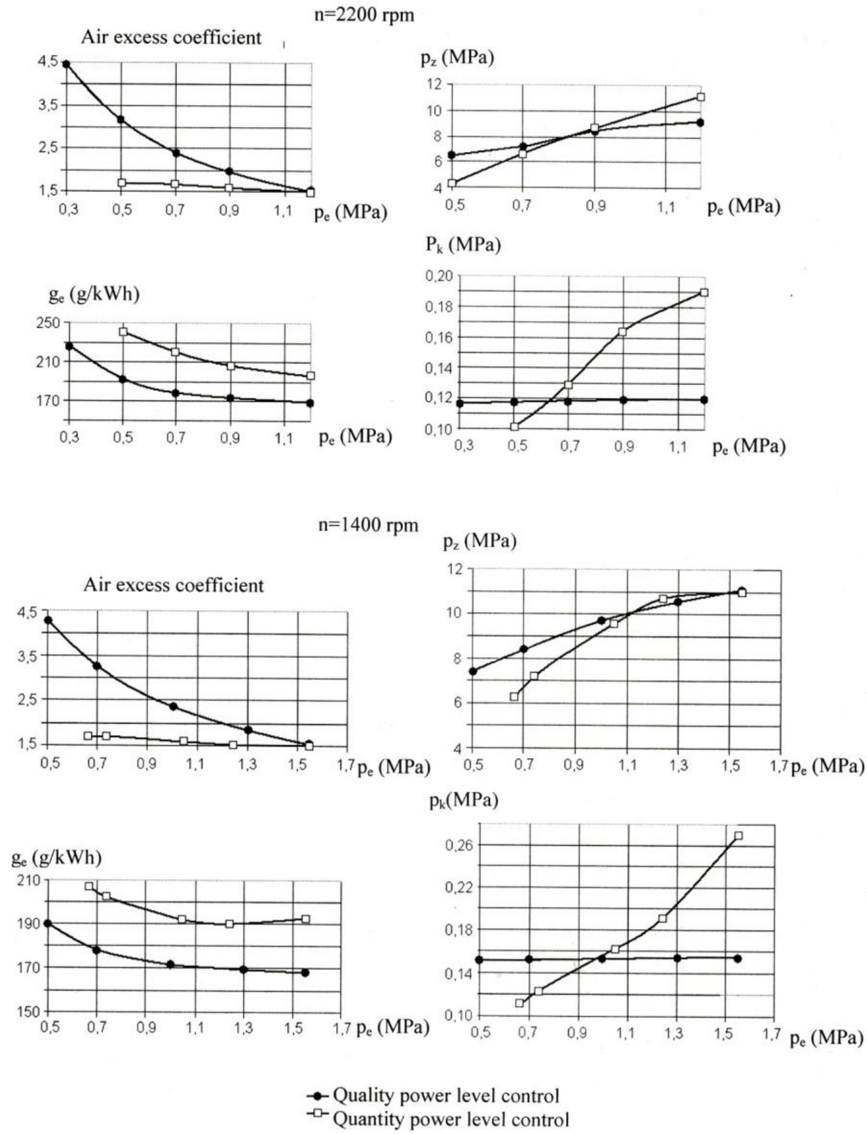

Fig. 1. Variation of calculated parameters of natural gas powered engines by load characteristics

Analysis of the above mentioned characteristics demonstrates that in case of quality power level control of the gas engine, the lowest values of the brake specific fuel consumption g_e are attained at both the engine speeds. The difference in g_e is of course higher at low loads (higher air excess coefficient α). The differences in other parameters are also linked with the nature of α variation.

One should note that equal values of the mean effective pressure were obtained in case of quantity power level control thanks to a higher boost pressure (a smaller turbine cross-section area was used).

Generally, it is possible to mark that quality power level control ensures the improvement of gas engines parameters.

For qualitative estimation of potential advantages of natural gas engines as regards their CO_2 emissions, calculations of CO_2 emissions were made for the above indicated KAMAZ diesel engine and four versions of natural gas engines designed on the base of the KAMAZ engine provided that these engines had equal fuel efficiency:

Condition of calculating CO_2 emissions:

1. Comparison of CO_2 emissions was made by the 13-stage cycle;
2. Low calorific value of diesel fuel – 42.56 MJ/kg;
3. Carbon content in 1 kg of diesel fuel – 0.872 kg;
4. Low calorific value of natural gas (taking into account the content of methane close to 100%) – 50 MJ/kg;
5. Carbon content in 1 kg of natural gas – 0.75 kg;
6. When computing the dioxide carbon (CO_2) emissions in the gas engine with the diesel compression ratio, the difference in calorific value of both the fuels was taken into account;
7. The assumption was taken that the heat input for all operating modes was equal.

Natural gas consumption per hour in the gas diesel to obtain the same heat input as in the diesel engine was calculated by equation:

$$G_{gaseng} = \left(G_{diseng} - G_{pilot} \times 30 \times n \times i \times 10^{-6}\right) \times \left(\frac{H_{U\,gas}}{H_{U\,dis}}\right),$$

where $G_{dis\ eng}$- diesel fuel consumption in the diesel engine (kg/h), G_{pilot} – cycle fuel delivery of the diesel fuel pilot portion in the gas diesel engine (mg/cycle), n – engine speed (rpm), $H_{U\ dis}$- low calorific value of diesel fuel; $H_{U\ gas}$- low calorific value of natural gas; i - number of cylinders (in our case, i = 8).

Calculations of CO_2 emissions were based on the content of carbon in the fuel. For the gas fuel, the content of carbon depends on its composition. The average results of six measurements carried out showed that the gas fuel available contained more than 98.5% of methane, other gases were: ethane, propane, butane, carbon dioxide and nitrogen.

When calculating CO_2 emissions for the base diesel engine KAMAZ 74051-320, we used data obtained earlier during engine tests.

The other engines were recalculated by their low calorific value using the data for diesel engine assuming that the engines considered had equal fuel efficiency.

The results of CO_2 calculations

The results of CO_2 calculations by the modes of the 13-stage engine cycle are shown in Tables 1, 2, 3, 4 (where k – weighting factor, accepted in compliance with the Rules R49 of the UN ECE).

The summary Table 5 indicates the values of specific emissions of dioxide carbon for the engines considered which shows the following:

- the decrease of CO_2 emissions in the gas engine with quality power level control and glow plug ignition was 26.8% compared with the diesel engine;
- the decrease of CO_2 emissions in the new generation gas engine was 25.5% compared with the diesel engine;
- the gas diesel engine with a Common Rail fuel injection system ensures the decrease of carbon dioxide emissions by additional 5.3% compared with the gas diesel engine having a direct injection fuel supply system. Even higher effect of using natural gas is ensured when comparing with petrol engine (Khatchiyan *et al.*, 2008).

Comparing the effects of decreasing emissions of the main greenhouse gas – carbon dioxide using two methods of achieving the fuel efficiency equal to that of the base diesel engine: the gas engine with the gas-air mixture ignition by a glow plug and the gas engine with the gas-air mixture ignition by a small pilot portion of a fine atomized diesel fuel, one can say that both the approaches ensure a close value of reducing the emissions of CO_2. Therefore, the choice between these two methods should be carried out taking into account other parameters:

1. Ensuring a stable operation with the fuel efficiency identical to that of a diesel engine in the whole range of performance modes of a vehicle.
2. The minimal development and production price and ensuring a reliable operation of the gas version of the base diesel

Based on the above stated and taking into consideration economic aspects, for carrying out the scientific-research work, we chose the working process of the natural gas engine with quality power level control and gas-air mixture ignition by a pilot portion of a fine atomized diesel fuel supplied by the Common Rail fuel system. It should be also mentioned that for automotive gas diesel engines, one should decrease heating of the injector nozzle, for example, by cooling it with circulating fuel.

Table 1. 13-stage cycle of the base diesel engine

n (rpm)	N_e (kW)	k	G_{fuel} (kg/h)	G_{air} (kg/h)	mCO_2, (g/h)	mCO_2*k, (g/h)	N_e*k, (kW)
600	0	0.083	1.10	215.10	3517	293	0
1400	18.299	0.08	7.10	547.00	22701	1816	1.464
1400	45.935	0.08	11.3	567.50	36130	2890	3.675
1400	92.13	0.08	19.9	653.10	63627	5090	7.370
1400	138.164	0.08	28.6	746.80	91444	7315	11.053
1400	184.39	0.25	37.8	849.70	120859	30215	46.098
600	0	0.0833	1.10	208.60	3517	293	0
2200	215.663	0.1	53.7	1561.2	171697	17170	21.566
2200	162.109	0.02	41.5	1450.6	132689	2654	3.242
2200	107.802	0.02	30.4	1339.5	97199	1944	2.156
2200	53.867	0.02	20.2	1122.0	64586	1292	1.077
2200	21.713	0.02	14.2	1046.7	45402	908	0.434
600	0	0.0833	1.10	208.60	3517	293	0
						∑mCO_2*k	∑N_e*k
						72173	98.136

Table 2. 13-stage cycle of the gas engine with quality power level control

n (rpm)	N_e (kW)	k	G_{fuel} (kg/h)	G_{air} (kg/h)	mCO_2, (g/h)	mCO_2*k, (g/h)	N_e*k, (kW)
600	0	0.0833	0.936	215.1	2575	214	0
1400	18.299	0.08	6.044	547.0	16620	1330	1.464
1400	45.935	0.08	9.619	567.5	26451	2116	3.675
1400	92.130	0.08	16.939	653.1	46582	3727	7.370
1400	138.164	0.08	24.344	746.8	66947	5356	11.053
1400	184.390	0.25	32.175	849.7	88482	22121	46.098
600	0	0.0833	0.936	208.6	2575	214	0
2200	215.663	0.1	45.709	1561.2	125701	12570	21.566
2200	162.109	0.02	35.325	1450.6	97143	1943	3.242
2200	107.802	0.02	25.876	1339.5	71160	1423	2.156
2200	53.867	0.02	17.194	1122.0	47284	946	1.077
2200	21.713	0.02	12.087	1046.7	33239	665	0.434
600	0	0.0833	0.936	208.6	2575	214	0
						∑mCO_2*k	∑N_e*k
						52839	98.136

Table 3. 13-stage cycle of the natural gas powered diesel engine (cycle fuel delivery 5 mg/cycle)

n (rpm)	N_e (kW)	k	G_{fuel} (kg/h)	$G_{gas'}$ (kg/h)	G_{air} (kg/h)	mCO_2^{dis} (g/h)	mCO_2^{gas} (g/h)	mCO_2^{dis}*k (g/h)	mCO_2^{gas}*k (g/h)	mCO_2^{summ}* k (g/h)	Ne*k (kW)
600	0	0.0833	0.0018	0	215.1	3453	0	287.6349	0	287.6349	0
1400	18.299	0.08	0.0036	1.753	547.0	16115	4822	1289.2	385.76	1674.96	1.464
1400	45.935	0.08	0.0036	5.329	567.5	16115	14653	1289.2	1172.24	2461.44	3.675
1400	92.130	0.08	0.0036	12.649	653.1	16115	34784	1289.2	2782.72	4071.92	7.370
1400	138.164	0.08	0.0036	20.054	746.8	16115	55149	1289.2	4411.92	5701.12	11.053
1400	184.390	0.25	0.0036	27.885	849.7	16115	76685	4028.75	19171.25	23199.75	46.098
600	0	0.0833	0.0018	0	208.6	3453	0	287.6349	0	287.6349	0
2200	215.663	0.1	0.0036	38.968	1561.2	25323	107162	2532.3	10716.2	13248.5	21.566
2200	162.109	0.02	0.0036	28.583	1450.6	25323	78604	506.46	1572.08	2078.54	3.242
2200	107.802	0.02	0.0036	19.135	1339.5	25323	52621	506.46	1052.42	1558.88	2.156
2200	53.867	0.02	0.0036	10.453	1122.0	25323	28745	506.46	574.9	1081.36	1.077
2200	21.713	0.02	0.0036	5.346	1046.7	25323	14700	506.46	294	800.46	0.434
600	0	0.0833	0.0018	0	208.6	3453	0	287.6349	0	287.6349	0
								∑ mCO_2^{dis}*k	∑ mCO_2^{gas}* k	∑ mCO_2^{summ}* k	∑Ne* k
								14606	42133	56739.83	98.136

Table 4. 13-stage cycle of the natural gas powered diesel engine (cycle fuel delivery 3 mg/cycle)

n (rpm)	N_e (kW)	k	G_{fuel} (kg/h)	G_{gas}' (kg/h)	G_{air} (kg/h)	mCO_2^{dis} (g/h)	mCO_2^{gas} (g/h)	$mCO_2^{dis}*k$ (g/h)	$mCO_2^{gas}*k$ (g/h)	$mCO_2^{summ}*k$ (g/h)	Ne*k (kW)
600	0	0.0833	0.00036	0.936	215.1	691	2574	58	214	272	0
1400	18.299	0.08	0.00072	5.186	547.0	3223	14260	258	1141	1399	1.464
1400	45.935	0.08	0.00072	8.761	567.5	3223	24092	258	1927	2185	3.675
1400	92.130	0.08	0.00072	16.081	653.1	3223	44222	258	3538	3796	7.370
1400	138.164	0.08	0.00072	23.486	746.8	3223	64587	258	5167	5425	11.053
1400	184.390	0.25	0.00072	31.317	849.7	3223	86123	806	21531	22337	46.098
600	0	0.0833	0.00036	0.936	208.6	691	2574	58	214	272	0
2200	215.663	0.1	0.00072	44.361	1561.2	5065	121993	506	12199	12705	21.566
2200	162.109	0.02	0.00072	33.976	1450.6	5065	93435	101	1869	1970	3.242
2200	107.802	0.02	0.00072	24.528	1339.5	5065	67452	101	1349	1450	2.156
2200	53.867	0.02	0.00072	15.846	1122.0	5065	43576	101	872	973	1.077
2200	21.713	0.02	0.00072	10.739	1046.7	5065	29532	101	591	692	0.434
600	0	0.0833	0.00036	0.936	208.6	691	2574	58	214	272	0
								$\sum mCO_2^{dis}*k$	$\sum mCO_2^{gas}*k$	$\sum mCO_2^{sum}*k$	$\sum Ne*k$
								2921	50826	53748	98.136

Table 5. Summary Table

Engine type		Specific CO_2 emissions (g/kWh)
1	Diesel engine	734.44
2	Natural aspirated gas engine with spark ignition and quantity power level control	624.00
3	Gas engine with glow plug ignition and quality power level control	538.30
4	Gas engine with quality power level control and supply of a pilot portion of diesel fuel 15 mg/cycle (direct injection fuel supply system)	578.176
5	Gas engine with quality power level control and supply of a pilot portion of a fine atomized diesel fuel 3 mg/cycle (Common Rail fuel supply system)	547.683

Conclusions

Comparison of operation parameters of the diesel engine with four versions of natural gas supplied engines demonstrated, that the gas engine with the glow plug ignition and quality power level control, and the gas engine with the quality power level control and supply of a pilot portion of a fine atomized diesel fuel by the Common Rail system, ensure the lowest level of CO_2 emissions (approximately by 26%) compared to the diesel engine on condition of equal amount of heat inputted into the cylinders.

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