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A theoretical study of military fuel combustion rate in diesel engines under high–altitude conditions

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1. Introduction

Alpine and its variable terrain relief have negative impact on the vehicles and their engines work: decreasing productivity, rising fuel costs and jets pollution, appearing burnt and varnish, intensive increasing of engines wear, that are not suitable for operation in alpine terrain, and decrease of service life of individual components and assemblies. In many countries there are mountains, where various equipment operates, so design of vehicles adapted for operation in the mountains acquires a wide range of needs. Motor vehicle operation in the mountains has been investigated by a number of scientists from Russia, Peru, Georgia, Kyrgyzstan, India and others.

This article discusses issues related to the use of the kerosene type fuel F–34 (F–35) in internal combustion engines (ICE) in Afghan alpine mountains, and the mountains influence on the ICE operation process. ICE operation process in alpine terrain is discussed according to international standard atmospheric indicators, data of baseline which at sea level are as follows: atmospheric pressure P_0 = 0,1013 MPa, atmospheric air temperature T_0 = 288 K. The annual average temperature gradient is 6.5°C per each 1000 meters above sea level.

Table 1

The main characteristics of the diesel fuel, the fuel F–34 (F–35) and the fuel used in Afghanistan

Parameter	Flash temperature, °C	Aromatics fractions, vol. %	Density, kg/m³, heat 15°C	Fuel evaporation temperature, °C: Initial	10%	20%	50%	90%	Final	Viscosity, mm²/s +40, °C	Alkalinity mg KOH/100 cm³	Setting temperature, °C	Cetan number	Elemental sulfur, % by weight	Mercaptan, % by weight	Fuel heat, MJ/kg
„Afghanistan fuel“	42	25	761.7	146.9	164.8	172.5	189.7	222.6	242.2	1.1	0.015	–54.6	41	0.056	0.003	42.9
Diesel fuel E class (Lithuania)	51	11	820–845	180	220		245–280	310–330	330–360	2.0–4.5	N/A	–15	51	0.035	0.005	42.5
F–34(F–35)	> 38	25	775–840			205	229	262	300	0.97–1.2	0.015	–47	42	0.3	0.002	42.8

In 2004 ”NATO Pipeline Committee” adopted the concept of NATO general policy of unified fuel. All NATO countries, including Lithuania, have ratified STANAG 4362 document. The value of this policy is to substitute the diesel fuel for diesel engines of military land vehicles and equipment by the fuel F–34 (F–35).

The factory settings of fuel high-pressure pump for the vehicles in Lithuanian Armed Forces a service at the mountains of Afghanistan are unchanged – what at means that with increasing of the height above sea level, the working mixture in the engines will be saturated with the fuel not burned completely in ICE cylinders. With such a phenomenon, in ICE cylinders at the end of compression stroke the fuel combustion processes are sluggish, the engine start–up characteristics become worse, the engine operating is more noisy, gas temperature at the end of the combustion cycle and during the expansion cycle are higher. Advantages of homogeneous fuel policy have been widely presented and discussed, but the future problems that may arise during the transition to the use of fuel F–34 (F–35), were not widely spoken. Lithuanian Armed Forces also did not know about the future problems. They emerged when performing the international commitments in Afghanistan, where the Lithuanian military contingent operates diesel engines using one type of the military fuel, received through logistical supply system. Properties of the fuel used are slightly different from the characteristics of the homogeneous NATO fuel F–34 (F–35). Characteristics and properties of the fuel used in Afghanistan are very different from diesel fuel and a bit different from the fuel F–34 (F–35). Differences in the characteristics of the fuel are presented in Table 1.

2. Calculation of military fuel combustion rate

Experience of technical operation in Afghanistan has highlighted the increased failure rate of the engines 1DH–FTE, GM 6.5L, the OM 366 LA and decrease in performance of overall engines reliability [1]. One of the of engine reliability indicators is its resource, which depends on the engine operating conditions. In the view of current theory of friction and wear [2], parts wear rate V_d is

$$V_d = f\left(P,V,C\right) \tag{1}$$

where P is normal pressure between the contacting surfaces, V is relative speed of movement of the rubbing surfaces, C is friction conditions.

With regard to car engines, it can be said that the main parameters characterizing operational conditions are normal pressure between the contacting surfaces, the engine crankshaft speed, lubrication conditions of the engine parts, of the used fuel properties and characteristics and climatic conditions.

Scientific studies have shown [3] that the intensity of wear of engine parts and engine resource is entirely dependent on the rate of pressure growth per angle of one degree of engine crankshaft rotation during fuel combustion process in the cylinders of diesel engine.

Increase rate of maximum pressure $(dP/d\varphi)_{max}$ and the rate of average pressure $(\Delta P/\Delta\varphi)$ during fuel combustion process in the cylinders of diesel engine is called the fuel burning rate. The increase in increase rate of the maximum pressure $(dP/d\varphi)_{max}$ and the rate of average pressure $(\Delta P/\Delta\varphi)$ causes increasing of the engine power and productivity, also increasing maximum pressure P_z of the diesel operation cycle, increasing loads of the engine crankshaft mechanism and piston-cylinder mechanical group, and the diesel work is accompanied by specific diesel noise sounds, typical for rapid combustion of diesel fuel. This process influences the wear of engine parts.

The crankshaft mechanism by its own structure is a mechanical system that consists of rigid elements, which, under gas pressure during fuel combustion, are subject to oscillations. This leads to a high velocity movement of complex engine parts, which is accompanied by shocks and increased strength in places of connection and touch. Impact loads damage the lubricating films, whereas more force at joining and touch points leads to increased friction between the rubbing moving surfaces. Scientific studies have shown that harmonic oscillations of diesel engine parts take place with the pressure change in the engine cylinders. In 500–2000 Hz frequency range amplitude of the oscillations increases with the maximum increment rate of pressure $(dP/d\varphi)_{max}$ and the maximum pressure of the engine operation cycle P_z. In this article theoretical evaluation of fuel combustion rate in diesel engines is based on the MADI methodology [4]. In this methodology indicators characterizing the processes of fuel ignition delay and rapid fuel combustion period when diesel is working with Afghanistan's fuel is calculated.

The rate of maximum $(dP/d\varphi)_{max}$ and average $(\Delta P/\Delta\varphi)$ pressures increment during engine fuel combustion process in the cylinders of diesel engine is calculated by the formula [4]

$$\left(\frac{dP}{d\varphi}\right)_{max} = \frac{6n10^{-3}}{\sqrt{K_T \rho}}\frac{P_Z - P_C}{\varphi_1}\left(i\tau_1 \frac{100}{C_N}\right)^{\frac{2}{3}} \tag{2}$$

$$\tau_1 = \varphi_1 / \varphi_{IN} \tag{3}$$

$$\left(\frac{\Delta P}{\Delta\varphi}\right) = \frac{P_Z - P_C}{\varphi_2} \tag{4}$$

where n is rotation speed of the engine crankshaft, min^{-1}; K_T is factor characterizing fuel performance; ρ is fuel density, g/cm^3; P_Z is maximum cycle pressure, MPa; P_C is air compression in the cylinders of end pressure, MPa; φ_1 is fuel ignition delay, deg.c.r.; i is the relative fuel evaporation rate during fuel ignition delay period; τ_1 is the ratio of fuel ignition delay period and fuel injection period; C_N is fuel cetan number; φ_2 is the period of fuel rapid combustion, deg.c.r. (deg.c.r. is angle of degree of engine crankshaft rotation).

The fuel density and temperature can be expressed by a linear relationship [5]

$$\rho = \frac{\rho_{15}}{1 + \beta\left(t_2 - t_{15}\right)} \tag{5}$$

where ρ_{15} is fuel density at temperature t_{15} = 15°C, g/cm^3; β is fuel volume expansion coefficient, 1/°C, ρ is fuel density under temperature t_2, g/m^3.[5]

Watson factor characterizing fuel performance

$$K_T = \frac{1.216\sqrt[3]{T_{50}}}{\rho_{15}^{15}} \tag{6}$$

where T_{50} is distillation temperature of 50% fuel volume, °K; ρ_{15}^{15} is fuel density at temperature 15°C, g/cm^3.

Fuel evaporation ratio is calculated as follows [4]

$$i = \frac{m_{VIK}}{g_{CK}} \tag{7}$$

where m_{VIK} is fuel quantity vaporized over fuel ignition delay period, kg; g_{CK} is fuel quantity, injected into engine cylinder, over a cycle, kg.

In determining the period of the first phase the model of relative fuel ignition delay [4] is used

$$\tau = \sqrt{6n10^{-4}}\left[\begin{array}{l} \dfrac{ln\left[\sqrt{\rho}\left(\dfrac{\varphi_{IK}}{K_T} - \Theta_{BT}\right)\right]}{a} + \\ + \left[\dfrac{A}{2}\sqrt{\rho} - \dfrac{\left(1 - \dfrac{\varphi_{IL}}{\varphi_{OK}}\right)}{K_T}\right]\dfrac{\sqrt{a_1 - 1}}{\Psi\varphi_{IK}} \end{array}\right] \tag{8}$$

where θ_{BT} is nondimensional temperature at the beginning of fuel injection; A is the factor of fuel properties; a, a_1 are diesel engine and fuel injection system structure weightings; Ψ is assessment factor of the ratio of physical and chemical rates; φ_{IL} is fuel injection period (using fuel injection system features of real engines 1DH–FTE, GM 6.5L, OM 366 LA), deg.c.r.; φ_{IK} is the factory fuel injection angles (fuel injection system angles of real engines 1DH–FTE, GM 6.5L, OM 366 LA), deg.c.r.

Fuel evaporation ratio with sufficient accuracy can be assumed $i = 0.55 \times 1.3 = 0.715$, because $i = 0.55$ is diesel fuel evaporation ratio [4], and evaporation ratio of fuel F–34 (F–35) used in accordance with the carried out research [6-8] is 30% higher than for the diesel fuel.

Non-dimensional temperature θ_{BT}, factor of fuel properties A; assessment factors of the structure of diesel engine and fuel injection system a, a_1, Ψ is assessment factors of the ratio of physical and chemical rates are calculated as follows

$$\Theta_{BT} = \frac{1}{\left(4.38 + 2.29\, lg\, T_{50}\right) \frac{T_{50}}{T_C} \sqrt{K_1} + 25\left(\frac{1}{C_N} - \frac{1}{100}\right)} \quad (9)$$

$$A = \frac{K_T T_{50}}{C_N\, 273} \quad (10)$$

$$a = \frac{K_Q}{\Theta_{BT}}\left(a_1 - 1\right) \quad (11)$$

$$a_1 = \frac{\left(V_{IP} - V_{DK}\right)\left(n_1 - 1\right) \varphi_{IL} C_V \lambda_H l_{0D} T_{IP}}{\varphi_{pp} i q_T V_{IP} K_1} \quad (12)$$

$$\Psi = \sqrt{a}\, e^{2a} \quad (13)$$

where T_{IP} is temperature in engine cylinder at the moment of fuel injection, K; K_Q is nondimensional heat transfer characteristic; V_{IP} is cylinder volume at the moment of fuel injection, m^3; V_C is the volume of cylinder combustion chamber, m^3; n_1 is compression ratio of polytrophic; C_V is air specific heat (heat capacity), KJ/kg K; λ_0 is excess air ratio at an altitude $H = 0$ m; l_{0D} is the quantity of air needed to completely burn one kilogram of the fuel, kg; q_T is the quantity of heat required to vaporize and overheat a kilogram of fuel by injection into the compressed air in engine cylinder at temperature T_C.

Special factor that affects engine performance in alpine terrain is lower air density, which thus reduces the air intake volume to the engine cylinder during the cycle, therefore assessment at the beginning of compression cycle at height H of air pressure P_{AH} is made by the empirical formula [3]

$$P_{AH} = \mu\left(P_0 - \frac{\Delta P_{A0}}{\beta}\right) \quad (14)$$

where P_0 and ΔP_{A0} are air pressure and loss of air at sea level $H = 0$ m; μ is factor of difference of temperatures; β is atmospheric pressure difference coefficient (Table 2).

In the case of the engines used in Afghanistan, when the settings of engine manufacturer that match the engine operation at sea level at its nominal load are not changed leads the loss of excess air factor. The change of this ratio rising up in to the mountains, with unchanged settings of fuel system set by an engine manufacture is evaluated by the equation [3]

$$\lambda_H = \lambda_0 \frac{\mu}{\sqrt{\beta}} \left(\frac{\pi_{KH}}{\pi_{K0}}\right)^{\frac{1}{n_H}} \quad (15)$$

where λ_H is excess air factor at altitude H above sea level, π_{KH} is air pressure increase rate in compressor above sea level, $H > 0$; $\pi_{k0} = P_{outlet}/P_{intlet}$ is air pressure increase rate in the compressor at altitude $H = 0$ m [9]; n_H is air compression polytrophic ratio in compressor.

Table 2

International Standard Atmosphere Data (ISO 2533:1975/ADD 2:1997) [3]

Altitude above sea level, m	Air pressure			Air temperature		Air density, kg/cm^3	$\mu = \frac{T_H}{T_0}$	$\beta = \frac{P_H}{P_0}$
	MPa	kg/cm^3	mm Hg	°C	K			
0	0.101	1.033	760.0	+15.0	288.0	1.225	1.000	1.000
500	0.095	0.972	715.0	+11.2	284.2	1.168	0.940	0.986
1000	0.090	0.917	674.4	+8.5	281.5	1.112	0.887	0.977
1500	0.085	0.864	635.0	+5.3	278.3	1.059	0.835	0.966
2000	0.079	0.811	596.5	+2.0	275.0	1.006	0.785	0.955
2500	0.075	0.763	562.0	–1.2	271.8	0.957	0.740	0.943
3000	0.070	0.715	525.9	–4.5	268.5	0.909	0.692	0.932
3500	0.066	0.671	493.0	–7.7	265.3	0.864	0.650	0.921

Nondimensional heat transfer characteristic (K_Q), heat amount required to vaporize and overheat a kilogram of the fuel by injection into the compressed air of the engine cylinder at temperature T_C (q_T), cylinder volume at the fuel injection moment (V_{IP}), fuel ignition delay (φ_1) and fuel rapid combustion period (φ_2) and cycle maximum pressure (P_Z) are calculated as follows

$$K_Q = \frac{i q_T}{C_V \lambda_0 l_{0D} T_C} \sqrt{K_1} \quad (16)$$

$$q_T = C_D\left(T_{50} - T_P\right) + L_{GD} + 0.5 C_D\left(T_{IP} - T_{50}\right) \quad (17)$$

$$V_{IP} = \frac{V_h}{2}\left[\frac{\varepsilon + 1}{\varepsilon - 1} - \cos\varphi_{PP} + \frac{\lambda_1}{4}\left(1 - \cos 2\varphi_{PP}\right)\right] \quad (18)$$

$$\varphi_i = \tau_i \varphi_{IL} \quad (19)$$

$$\tau_i = \frac{\varphi_i}{6n} \quad (20)$$

$$\varphi_2 = \left(\frac{C_N}{100}\right) \rho \left(\frac{\varphi_{IL}}{i}\right) \quad (21)$$

$$P_Z = P_C + 5.39 \times 10^{-4} \frac{m_{VIK} H_Q \left(n_1 - 1\right)}{V_C} \quad (22)$$

where H_Q is fuel calorific value, kJ/kg; P_C is air pressure in the engine cylinder at the end of compression stroke, MPa; λ_1 is ratio of radius length of the crankshaft rotation and length of crank; L_{GD} is heat of making of vapor, kJ/kg; T_P is fuel initial temperature, K; C_D is fuel specific heat, kJ/(kg K).

3. Summary of theoretical research results

Taking into account the differences between diesel fuel and the fuel used in Afghanistan, given in Table 1, we can see that mostly they differ by fractional composition, viscosity and cetan number.

The nature of diesel engine operation depends on the used fuel fractional composition and cetan number. For burning the fuel of lighter fractional composition, less air is required; less time is required for preparing a flammable mixture, also. Such combustion of a mixture causes the loud diesel engine work – this can be explained as: at the moment of fuel ignition a significant amount of fuel vapor is in engines cylinder, the combustion of it is accompanied by an excessive pressure increase rate for 1° of the engine crankshaft rotation during combustion process and specific knock in the engine. The main indicator of noisy engine working is rate of maximum $(dP/d\varphi)_{max}$ and average $(\Delta P/\Delta\varphi)$ pressures increase rate during the engine fuel combustion process in the cylinders of diesel engine. The rate of pressure of many of these engines must not exceed the standard numbers $(dP/d\varphi)_{max} < 1.5 – 2.0$ MPa and $(\Delta P/\Delta\varphi) < 0.4 – 0.6$ MPa. Influence of fuel fractional composition on engines of different types is different (see Fig. 1). It is observed when investigating the three types of diesel engines 1DH–FTE, GM 6.5L, OM 366 LA.

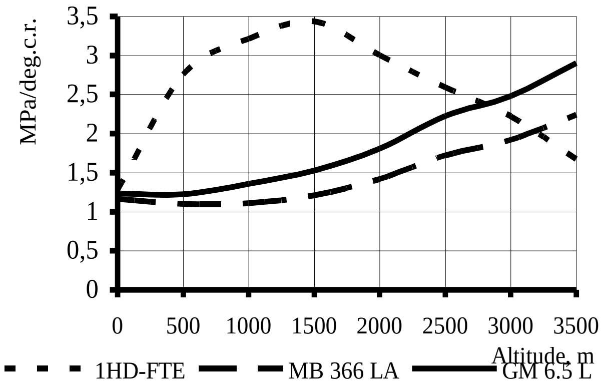

Fig. 1 Dependence of the rate of maximum pressure increase on altitude above sea level for engines 1DH–FTE, GM 6.5L, OM 366 LA at the nominal load during the combustion cycle

Compared with the engine 1DH–FTE with direct fuel injection, having a bulk combustible mixture preparation, the engine GM 6.5L with the swirl chamber and the engine OM 366 LA with axial and radial air turbulence for combustible mixture preparation are less sensitive to fuel with the light fractions. Fuel viscosity and fuel density describes the process of fuel evaporation and mixture preparation, fuel torch shape and structure, drops size, spray distance in the engine combustion chamber depend on them. Lower viscosity of the fuel increases the fuel penetration between the ram and cylinder bushings, this reduces the amount of fuel injected into the engine combustion chamber during the cycle. Decreases pressure of fuel injection in pipelines of high-pressure in engine fuel injection system – this increases the fuel injection delay period to the angle of 2–4° turn of the crank.

Decrease in fuel quantity injected by high-pressure fuel pump into the engine combustion chamber during the cycle is due to a lower fuel density, lower viscosity and greater degree of compression.

When rising in the mountains above sea level the preparation of fuel mixture and combustion processes is more complicated. In the mountains the air pressure (P_{AH}) at the beginning of the compression cycle is significantly reduced and accordingly the air pressure in the compression cycle (P_C) in the engine cylinder becomes less. This decrease in pressure negatively affects the quality of fuel injection and preparation of the combustion mixture. Two factors – excess air ratio (λ_H) and air pressure (P_C) in the engine cylinder – define the change of optimal fuel parameters of fuel high-pressure pump (fuel supply angle and injection start-up of fuel pressure). With the unchanged factory settings of fuel high-pressure pump fuel ignition delay period τ_1 (Fig. 2) and fuel combustion process period φ_2 increase, fuel combustion process expands into the expansion cycle and increases in time. The latter is associated with a relatively larger rapid combustion process $(dP/d\varphi)_{max}$, (Fig. 1), but with obvious pressure decrease in the combustion cycle P_z (Fig. 3), as well.

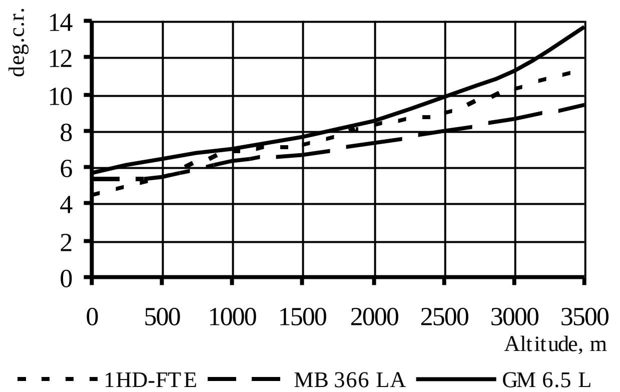

Fig. 2 Dependence of fuel ignition delays on altitude above sea level for engines 1DH–FTE, GM 6.5L, OM 366 LA at the nominal engine load

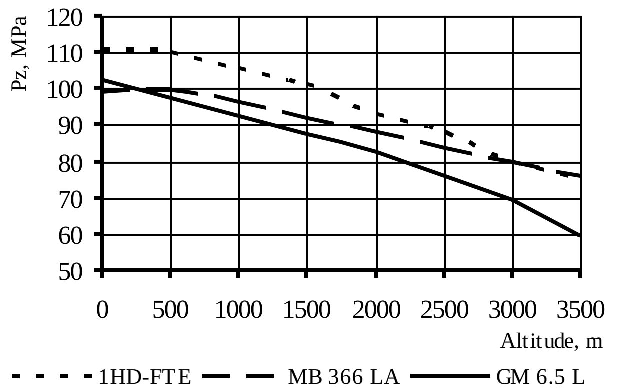

Fig. 3 Dependence of combustion cycle of maximum pressure on altitude above sea level for engines 1DH–FTE, GM 6.5L, OM 366 LA, at nominal engine load

4. Conclusions

Following the theoretical assessment of combustion rate of the fuel F–34 (F–35) substitute in diesel engines in high–altitude conditions, we can state that its use is complicated, operation of the engines is accompanied by too fast fuel combustion, occurring in loud engines work, an increase of delayed fuel ignition period, and a decrease in effective pressure of combustion cycle.

Minimum factors, able to improve engine performance, is changing of diesel power system, i.e. changing of fuel high-pressure pump factory settings: fuel injection angles, cyclic fuel and air intake volume.

The engines in which this fuel will be used must be developed and designed exactly for that type of fuel or have adaptation possibility if such changes occur, as the engines operated in Afghanistan react differently to the changes in the mountain climate and physical and chemical fuel properties.

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DYZELINIŲ VARIKLIŲ KARINIŲ DEGALŲ DEGIMO SPARTOS AUKŠTIKALNIŲ SĄLYGOMIS TEORINIS TYRIMAS

R e z i u m ė

Straipsnyje teoriškai tiriama Afganistano kalnuose eksploatuojamuose dyzeliniuose varikliuose 1DH–FTE, GM 6.5L, OM 366 LA naudojamo karinių degalų F–34 (F–35) pakaitalo, vadinamo Afganistano kuru, degimo sparta, esant nepakeistai gamyklos kuro tiekimo reguliavimo sistemai. Nustatyta, kad naudojant šiuos degalus kyla nemažai problemų, susijusių su dyzelinio variklio degalų degimo procesu, kuris pasireiškia degalų užsiliepsnojimo ir degalų degimo sąlygų blogėjimu, esant pernelyg dideliam slėgio prieaugio greičiui 1º variklio alkūninio veleno pasisukimui, bei ryškiu degimo ciklo slėgio mažėjimu. Šie pokyčiai atsiranda dėl kalnų klimato ir fizinių bei cheminių naudojamų degalų savybių.

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A THEORETICAL STUDY OF MILITARY FUEL COMBUSTION RATE IN DIESEL ENGINES UNDER HIGH–ALTITUDE CONDITIONS

S u m m a r y

The paper presents a theoretical study of combustion rate of the kerosene type fuel, as a substitute for the military fuel F–34 (F–35), used in the diesel engines 1DH–FTE, GM 6.5L, the OM 366 LA operated in the mountains of Afghanistan, with unchanged regulation settings of the factory fuel supply system. Fuel assessment showed that the fuel caused many problems, associated with fuel combustion process in diesel engine; this leads to deterioration of conditions of fuel ignition and fuel combustion with the excessive pressure increase rate for 1° of the engine crankshaft rotation and strong combustion cycle pressure drop. These changes are the result of mountain climate and the physical and chemical properties of the fuel used.

Keywords: engine, fuel, ignition delay, mountain

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