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EVALUATION OF EMISSION CHARACTERISTICS OF GAS TURBINE ENGINES USING ALTERNATIVE FUELS

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Abstract

The comprehensive analysis of the emissions of gas turbine engines operating on kerosene and some alternative fuels is considered. It is shown that the notable reduction in the emissions of traditional pollutants NO_x, CO and CO_2 can be expected for burning of biofuels. However, in this case, combustor can produce greater amounts of aldehydes and application of alternative fuels requires more careful consideration concerning the environment impact.

1 Introduction

For past decades the problem of aviation impact on global climate and ozone depletion has been of great concern to the experts engaged in the field and policymakers. Though, the aviation engines produce much smaller amounts of gaseous and particulate pollutants than the surface sources (transportation systems, power plants, industry and etc.), the potential role of aviation in the influence of anthropogenic factors on the atmospheric processes can be significant. For example, aviation-emitted carbon dioxide (CO_2) contributes 1.6% to total anthropogenic radiative forcing (RF). Such gaseous species as nitrogen compounds (NO, NO_2, N_2O, HNO_2, HNO_3), water vapor, sulfur compounds (SO_2, SO_3, H_2SO_4), organics (mostly CH_2O, CH_3OH, C_2HO), unburned hydrocarbons (CH_4, C_2H_2, C_2H_4) and particulate matter such as soot and volatile (organic and sulfate) aerosol particles contribute to climate effects and are responsible for 4.9% of total anthropogenic RF. As is known, volatile aerosol particles can influence directly on radiating forcing, and indirect effect occurs via their influence on heterogeneous chemistry. As well, volatile particles can participate in contrail formation through the mechanism of the activation of primary hydrophobic emitted soot particles.

The other important issue in the problem of aviation impact on the atmosphere is the reduction of the emissions of greenhouse gases (mostly CO_2 and H_2O). There exist only two possibilities to reduce greenhouse gas emissions. The first one is to ensure the growth in fuel efficiency of aircraft, in which, in spite of the increase in air traffic, there is a reduction in the total consumption of aviation fuel. To-date, the growth of aircraft fuel efficiency is of 1% per year only. In order to reduce greenhouse gas emissions in the face of rising air traffic, the airlines must be more than three times faster increase in fuel efficiency that is very problematic. The second possibility is the use of alternative fuels. Combustion products of such fuels are more meet the requirements of environmental protection legislation in comparison with those of traditional aviation fuels. It is worth noting that, today, significant progress in the field of production of alternative fuels has been made. In particular, the technologies of synthetic fuel production from coal based on the Fischer-Tropsch (FT) process, natural gas and biomass were developed. As well, some experience has been achieved in the field of production of condensed gas fuels from natural gas and oil.

Today, the technology of synthetic fuel production from coal based on Fischer-Tropsch process is widely used. The FT-fuel has larger combustion heat than that of aviation kerosene. Moreover, carbon mass fraction in FT-fuel is lower than that for kerosene and, therefore, the total emission of CO_2 decreases by several percents upon replacement of kerosene by FT-fuels. However, the process of synthetic FT-fuel production is itself accompanied by additional emission of CO_2, and total emission of CO_2 can be larger than that during aviation kerosene burning. Therefore, FT-fuel cannot ensure the decrease of CO_2 emission.

The liquefied natural gas (LNG) is free from this shortage. Moreover, the reduction of CO_2 emissions from combustion of LNG will be more significant than that for synthetic fuel burning, since, first, the mass fraction of carbon in methane – the main component of LNG – is smaller than that for FT-fuels, and second, LNG has a higher calories and, therefore, the production of the same capacity would require the use of LNG less fuel. The same is valid, although to a lesser extent, for liquefied gases (ASKT fuel), in the case where their composition prevail not too heavy hydrocarbons - propane and butane.

It seems, however, obviously that the replacement of jet fuel by LNG or by any other synthetic fuels produced from minerals is not able to solve fundamentally the problem of carbon dioxide exhaust. Most experts agree that the most promising fuel, in terms of reducing greenhouse gas emissions, is a biofuel because such a fuel has a unique property. This property is that the combustion of biofuel releases into the atmosphere the same amount of CO_2, which was previously absorbed by the crude plant during photosynthesis of glucose. In addition, biofuel has the other very important advantage: it is virtually free of sulfur and aromatics.

This paper addresses the comprehensive analysis of emission characteristics of gas turbine engines with kerosene and alternative fueled-combustors (including liquefied natural gas, synthetic fuel and various biofuels).

2 Alternative fuel characteristics

The change in the emission characteristics of gas turbine engine due to replacement of aviation kerosene by the alternative fuels was evaluated by the use of the seven types of fuel: LNG, bio-ethanol, biometanol, biobutanol, dimethyl ether, biodiesel from soybean oil and biodiesel from rapeseed oil. The main physical and chemical properties of these fuels and jet fuel Jet-A are presented in table 1. The method used for calculating the specific heat capacity H_u was described in [1]. The standard enthalpy of jet fuel ΔH_f^0 is highly dependent on its

Table 1. Some physical and thermo-chemical properties of modern alternative fuels and aviation kerosene Jet-A

Fuel	Chemical formula	Mass fraction of carbon, %	Boiling temperature T_v, K	Enthalpy of formation ΔH_f^0, kJ/kg	Mass stoichio-metric ratio Km_0, kg(air)/kg(fuel)	Specific heat capacity H_u, MJ/kg	Temperature of combustion exhaust at normal conditions T_c, K	Operating capacity of combustion products RT_c, kJ/kg
Cryogenic methane	CH_4	74.9	111.7	-5439	17	49.3	2211	670
Biomethanol	CH_3OH	37.5	337.8	-7456	6.4	19.9	2155	654
Bioethanol	C_2H_5OH	52.1	351.5	-6012	8.8	26.8	2201	655
Biobutanol	C_4H_9OH	64.8	390	-4425	11	33.1	2239	660
Dimethyl ether	C_2H_6O	52.1	248	-4528	8.8	28.3	2267	676
Biodiesel (soybean)	$C_{64.3}H_{117.7}O_{6.8}$	77.22	-	-2423	12.3	37.1	2277	660
Biodiesel (rapeseed)	$C_{64.2}H_{118.8}O_{6.8}$	77.21	-	-2399	12.4	37.2	2279	661
Jet-A	$C_{11}H_{21}$	86.2	440-540	-1639	14.4	43.1	2281	663

Table 2. Chemical composition of main biodiesel fuels

Chemical composition	Biodiesel (soybean) $C_{64.3}H_{117.7}O_{6.8}$	Biodiesel (rapeseed) $C_{64.2}H_{118.8}O_{6.8}$
Methyl palmitate $C_{17}H_{34}O_2$	8	4.3
Methyl stearate $C_{19}H_{38}O$	3.5	1.3
Methyl oleate $C_{19}H_{36}O_2$	25	59.9
Methyl linoleate $C_{19}H_{34}O_2$	55	21.1
Methyl linolenate $C_{19}H_{32}O_2$	8.5	13.2

chemical composition. According to [2], the enthalpy of the most common in commercial aviation kerosene Jet-A is -1639 kJ / kg.

Like kerosene, biodiesel is a mixture of individual compounds: fatty acid methyl esters obtained by esterification of rapeseed or soybean oils. The chemical composition of biodiesel fuel considered in the paper is listed in table 2 [3].

3 Methodology

For the evaluation of pollutant emission two methodologies were used.

The first one is the estimations on the base of equilibrium thermodynamic approach [4, 5]. The emission characteristics calculated by such way are equilibrium. Because the fuel-lean mixtures are burned in combustors of gas turbine engines, the emission can be determined not for all pollutants. For example, unburned hydrocarbons and soot are absent in combustion product in this case. It was shown earlier [6] that concentrations of such ecologically harmful species as NO, NO_2, CO, N_2O, HONO, and HNO_3 don't change substantially in the engine internal duct from combustor to nozzle exit. Therefore, the estimations of equilibrium emission characteristics of these species at the engine exit come to the thermodynamic calculation of the composition of combustion exhaust. Computations were carried out at given values of pressure in combustor and air temperature behind the compressor as well as at such value of fuel-to-air equivalence ratio ϕ that ensures the given gas temperature at the combustor exit.

The second methodology is extremely nonequilibrium. It is known, that the actual concentrations of many species can differ substantially (by several orders of magnitude) from their equilibrium values [7]. The main reason of such distinction is the sharp decrease of reaction rates due to mixing the combustion products with cold secondary air [7]. To evaluate this effect on the engine emission characteristics it was assumed that gas composition at the combustor exit is determined the equilibrium composition of hot gas from combustion zone and composition of secondary air. The fuel-to-air equivalence ratio ϕ in combustion zone was chosen to be equal unity. The flow rate of secondary air was determined by such a way to ensure the needed value of ϕ at the combustor exit.

Thus, the emission characteristics were estimated for two limiting situation: fully equilibrium combustion products and fully nonequilibrium ones due to their cooling in mixing zone.

4 Results

Computations were performed for turbojet engine with following parameters: the pressure in combustor is 2144.8 kPa, air temperature behind the compressor is 755.6 K, gas temperature at the combustor exit is equal to 1512 K. These values approximately correspond to parameters of turbojet engine that were considered in framework of project HISAC [6].

First of all, for different fuels it is necessary to determine the composition of combustible mixture which can provide the given value of temperature at the combustor exit. Fig. 1 shows the air-to-fuel ratio for different fuels satisfying this condition. One can see that for all considered alternative fuels (except cryogenic methane) the increase in the relative proportion of the fuel in the combustible mixture takes place. This caused by the lower specific heating capacity of alternative fuels compared to kerosene (see table 1). The most

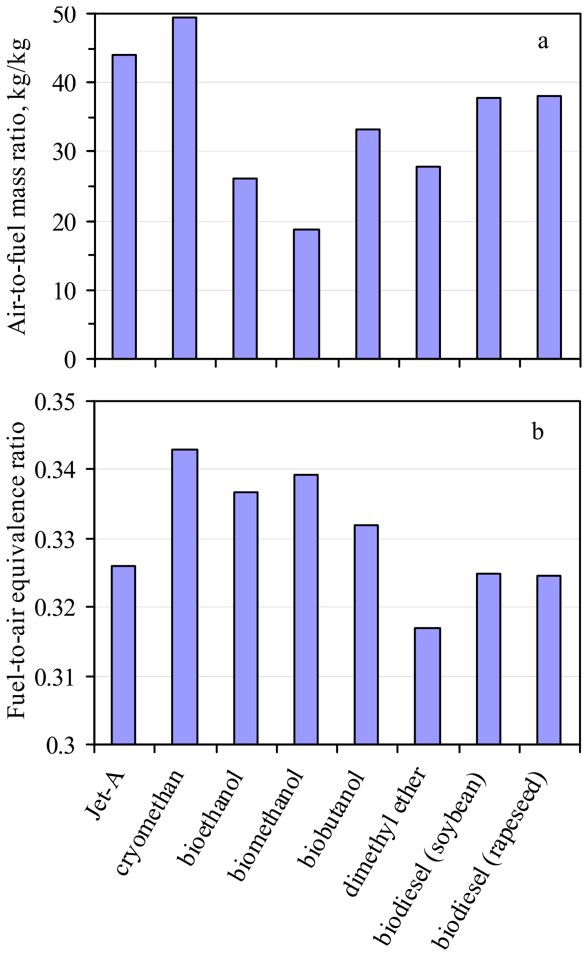

Fig. 1. Air-to-fuel mass ratio (a) and fuel-to-air equivalence ratio (b) in combustor operating on different fuels to ensure the same value of power.

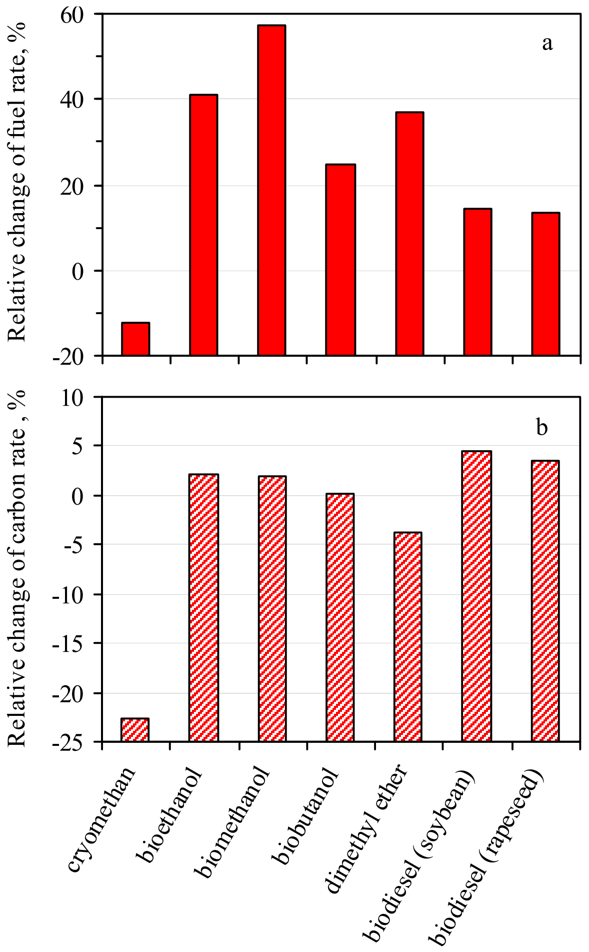

Fig. 2. The relative change in fuel rate (a) and carbon rate (b) upon replacement of kerosene by different alternative fuels.

increase of the fuel fraction is expected for biomethanol because it has the least combustion heat.

Fig. 2a shows the change in fuel rate when kerosene is replaced by one of the alternative fuels. It is seen the increase of fuel rate for all alternative fuels (except cryogenic methane): for biodiesel this increase is 12-13%, for biomethanol it achieves to ~60%. The most acceptable fuel from the viewpoint of fuel economy is cryogenic methane that gives the reduction of fuel rate about of 12%. Fig. 2b depicts the change on the total carbon rate when alternative fuel is used instead of kerosene. One can see that it is possible to reduce the carbon rate for cryogenic methane (by about of 20%) that is explained by its higher fuel economy (fig. 2a) and lower proportion of carbon in the fuel compared to kerosene. For all other alternative fuels, the carbon rate increases.

According to the change of carbon rate, the CO_2 emission decreases (for cryogenic methane and dimethyl ether) or increases (for all other fuels). Fig. 3 depicts the relative change in emissions of CO_2 and H_2O determined as the ratio of species mass rates for the combustor operating on given alternative fuel and kerosene. All considered fuels ensure the increase of water vapor emission: minor value for biodiesel and much higher for cryogenic methane, biomethanol and bioethanol. This means that in the exhaust plume of the engine operating on such fuels, the large value of water vapor supersaturation will appear that can increase the rate of aerosol particle formation.

Fig. 4 shows the relative change in emissions of NO_x, CO, N_2O, HONO и HNO_3

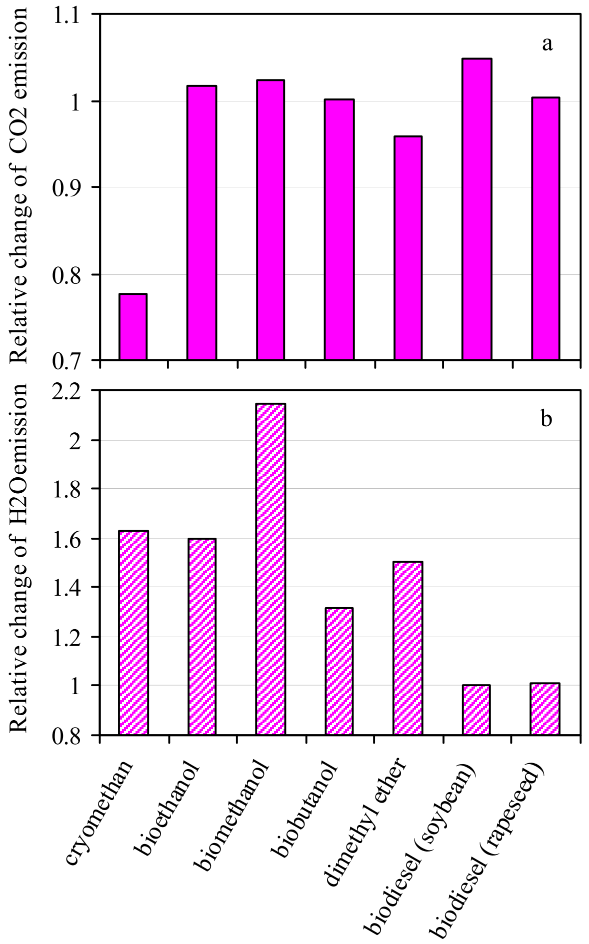

Fig. 3. The relative change of CO_2 (a) and H_2O (b) emissions upon replacement of kerosene by different alternative fuels.

due to replacement of kerosene by different alternative fuels. One can see that for all considered fuels the change in equilibrium concentrations of NO and NO_2 does not occur, because the equilibrium concentration of nitrogen oxides in fuel-lean mixture mostly depends on the gas temperature, which is identical for all fuels in our calculations. At the same time for extremely nonequilibrium case, the essential decrease of nitrogen oxides emission takes place. This is explained by the fact that the formation of nitrogen oxides occurs in a high temperature zone of combustor, and the kerosene combustion products have the highest temperature (see. table 1), and, hence, the largest concentrations of NO and NO_2. For all other fuels, the temperature in combustion zone (where $\phi=1$) is lower, that leads, to the smaller concentrations of NO and NO_2 at the combustion exhaust. The decrease in N_2O emission in nonequilibrium case is explained by the same reasoning.

It is known that the real concentration of CO in combustion products is several orders of magnitude higher than its equilibrium value [7]. Therefore, the nonequilibrium model must be used to estimate the change in CO emission due to replacement of kerosene by alternative fuels. According to estimations, the decrease in CO emission must occur for all fuels except biodiesel.

It is very important to estimate the emission of aldehydes, first of all formaldehyde, and soot. It is impossible to do in framework of equilibrium approach. However, one can evaluate the change in soot and formaldehyde emissions compared to kerosene combustion using on combustion of the fuel-rich mixtures. The computations showed that it is possible to expect the decrease of equilibrium concentrations of solid carbon when kerosene is replaced by biofuel. This decrease was also observed in experiments [8]. At the same time, such a replacement results in the increase of formaldehyde emission.

5 Conclusions

The use of biomethanol and biomethanol seems to be not efficient due to a substantial decrease in the engine fuel economy. The replacement of aviation kerosene by cryogenic methane decreases CO_2 emission by more than 20% with the simultaneous increase (by a factor of 1.6) of the emissions of water vapor, HNO_2 and HNO_3. One can expect the decrease of the emission of nitrogen oxides due to lower temperature in the flame front zone in combustor. The most decrease of NO_x emission can take place upon using cryogenic methane, biomethanol and bioethanol instend of kerosene. The replacement of aviation kerosene by biofuel makes it possible to decrease the soot emission. However, the aldehydes emission increases in this case.

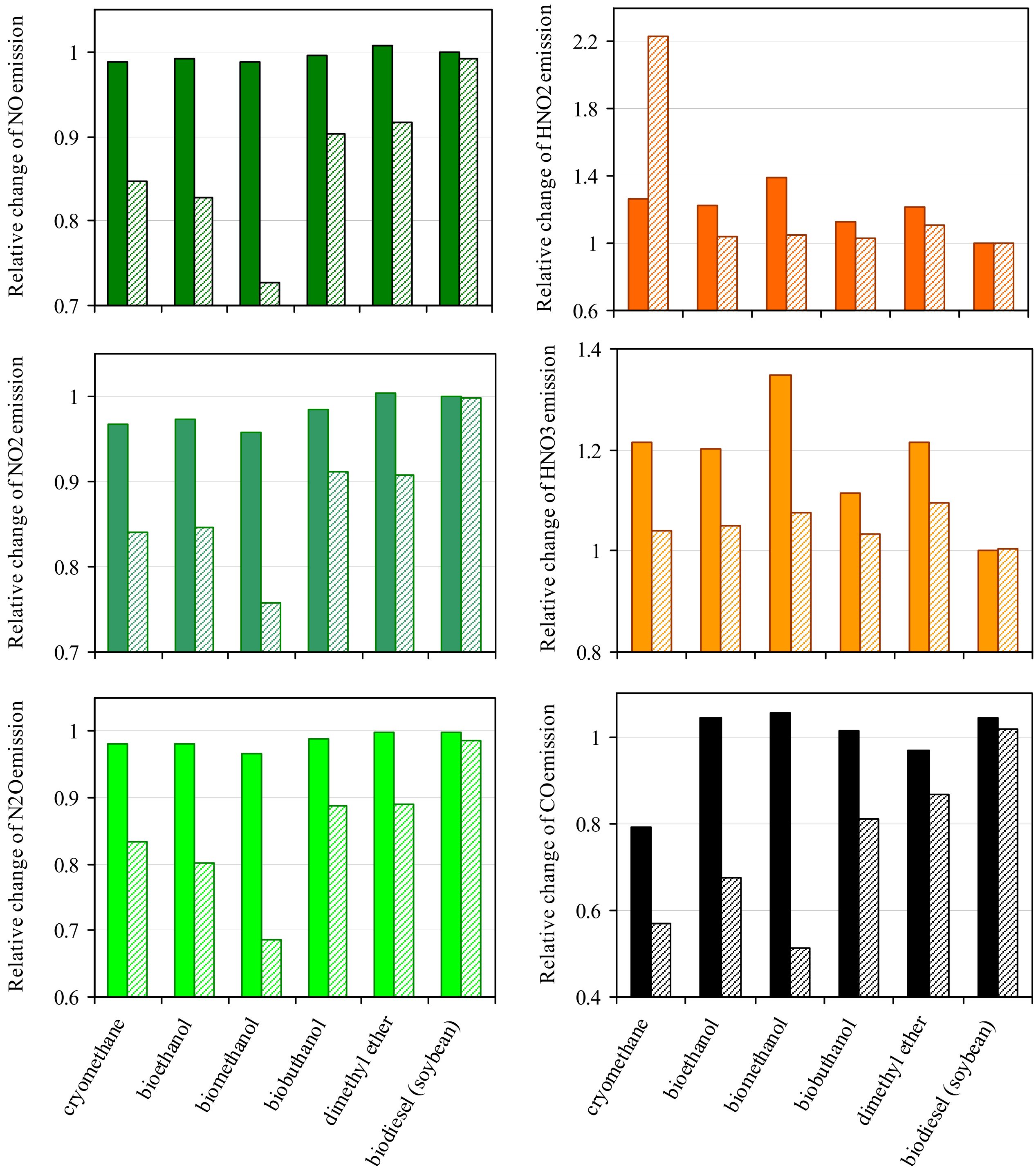

Fig. 4. The relative change in NO, NO_2, N_2O, HNO_2, HNO_3 and CO emission upon replacement the kerosene by alternative fuels.

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