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EVALUATION OF ALTERNATIVE JET FUELS' EFFICIENCY FOR REDUCTION OF EXHAUST GASES EMISSIONS

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Abstract. The work is devoted to the study of environmental efficiency of the use of alternative aviation fuels, with the aim of reduction of the level of exhaust gases emission. To achieve this, aviation fuels were mixed with rapeseed and camelina oils based biocomponents. To begin with, the physico-chemical properties of the tested fuel samples were compared with those of traditional jet fuel and standard requirements. Then composition of the chemical elements for all fuel samples was investigated and the CO_2, H_2O, SO_2 emission indices for each fuel sample were calculated from the data obtained. On the basis of all the data we obtained, we calculated the exhaust gases emissions for each fuel sample and concluded that the effectiveness of the use of alternative aviation fuels to reduce the level of exhaust gases emissions.

Keywords: jet fuel, alternative fuel, rapeseed oil, camelina oil, fatty acids esters, emission, exhaust gases, emission index, landing-take-off cycle.

Introduction

Nowadays, the problem of reducing emissions of aircrafts exhaust gases into the atmosphere is crucial and at the same time difficult for humanity. First of all, this is due to the fact that volume of passenger air transport is increasing every year. At this rate of increasing demand for air travel, it is difficult to find and implement quickly methods for reducing exhaust gases emissions. One of the most realistic and promising methods of reducing exhaust gases emissions is introduction of alternative aviation fuels (AAF) in the aviation sector, which should reduce exhaust gases emissions.

Literature overview

The contribution of jet fuel (JF) to the total energy consumption in transport is expected to increase from 11% to 14% in the next 20 years. More than 99% of airline emissions are generated by the combustion of JF, and the emissions from international aviation, which account for approximately 65% of global aviation fuel consumption, are expected to increase to 1.1–1.5 bln t CO_2 by 2035. Aircraft also emits other gases and particles that have climate impacts (Hileman, Stratton 2014).

According to the researches, exhaust gases from aircrafts tipically contain about 200 harmful substances. The main pollutants among them are carbon dioxide, methane, soot, sulfur oxides, carbon monoxide, oxides of nitrogen, unburnt hydrocarbons and others (Yakovlieva *et al.* 2019).

The share of CO_2 emissions from aviation in comparison with other sources of CO_2 emissions is about 2% and this value is growing rapidly (Yakovlieva *et al.* 2019). Experts estimate that, by 2050, air travel will cause up to 20% of harmful emissions worldwide, unless leverage is reduced. Compared to the share of emissions from road transport, aviation today has less environmental impact, but today the automotive industry is rapidly finding and implementing measures to reduce exhaust gases emissions, and the aviation industry is not experiencing such a high rate of development in this respect (Hileman, Stratton 2014; Liu *et al.* 2013).

The public and political pressure on the aviation sector concerning reduction of greenhouse gases emission is continuously rising during last years, particularly in Europe after the extension of the European Union Emission Trading Scheme (ETS) to the air transport sector since January 2013. For this reason, the aviation industry has committed itself to reduce net CO_2 emissions of 50% by 2050 compared with 2005 levels (Kallio *et al.* 2014).

To facilitate carbon-neutral growth of international civil aviation emissions after 2020, ICAO introduced the *Carbon Offsetting and Reduction Scheme for International Aviation* (CORSIA). CORSIA is a global market-based measure system to offset international aviation emissions growth by the following measures – technological improvements, operational efficiency measures, and AAFs (Yakovlieva *et al.* 2019).

Technological and operational improvements alone cannot reduce aviation emissions enough to meet ICAO's target of carbon-neutral growth. ICAO's findings indicate that the bulk of the emissions reductions needed for international aviation would have to come from a transition to AAFs.

This situation is forced by international organizations on one hand in order to increase environmental requirements for aviation fuels, and on the other hand to promote the introduction of alternative environmentally safe fuels. The *International Air Transport Association* (IATA) has set a goal of reducing CO_2 emissions from air transport by 50% by 2050 (IATA 2011).

The purpose of this work is to determine the effectiveness of the use of AAFs based on plants oils to reduce the emission of exhaust gases from aircrafts.

In order to reach the set purpose, the following tasks have to be done:

– Study the basic physical-chemical properties of samples of AAFs and evaluate them according to requirements to conventional JF;
– Determine emission indexes of main aircraft exhaust gases (CO_2, H_2O and SO_2);
– Calculate amount of exhaust gases emissions per one standard landing take-off cycle;
– Evaluate effectiveness of AAFs use for reduction of exhaust gases emissions.

Study of the basic physical-chemical properties of AAFs blended with bio-additives

In this paper, we investigated AAF, based on bio-additives obtained by esterification of plants oils (rapeseed and camelina) with simple alcohols, namely:

– Fatty acids methyl esters (FAME) of rapeseed oil;
– Fatty acids ethyl esters (FAEE) of rapeseed oil;
– Fatty acids ethyl esters (FAEE) of camelina oil;
– Fatty acids iso-butyl esters (FAIBE) of camelina oil;

Thus, as the purpose of the study is to investigate the emission of exhaust gases from alternative aviation fuels (a mixture of conventional JF and bio-additive), the research were performed for AAF with a mass fraction of bio-additive 10% and 20%. Some of the bio-additives and corresponding fuel samples were investigated in the previous studies (Yakovlieva *et al.* 2017).

At the first stage of the research, we have studied experimentally the main physical-chemical properties that are typical for aviation fuels: density, viscosity, pour point, net heat of combustion and flash point (Table 1).

Table 1. Physical-chemical properties of the studied fuel samples.

Fuel Samples	Density at t = 20 ºC, kg/m^3	Kinematic viscosity, mm^2 /s, at t = 20 ºC, no more	Pour point, ºC, no more	Flash point, ºC, not less	Net heat of combustion kJ/kg, not less
Requirements of ASTM D1655	775-840	8.0	-47	38	42,800
JF of grade Jet A-1	797.14	1.5	-59	43	43,211
JF+10% FAME of rapeseed oil	803.22	1.685	-57	43	42,569
JF+20% FAME of rapeseed oil	810.83	1.934	-55	44	41,919
JF+10% FAEE of rapeseed oil	797.14	1.734	-56	44.5	42,595
JF+20% FAEE of rapeseed oil	811.81	2.025	-54	45.5	41,971
JF+10% FAEE of camelina oil	799.63	1.803	-62	44	42,613
JF+20% FAEE of camelina oil	807.27	1.997	-55	44.5	41,997
JF+10% FAIBE of camelina oil	800.08	1.726	-63	45	42,776
JF+20% FAIBE of camelina oil	807.15	1.943	-57	46.5	42,453

From the table data, we can conclude that samples of blended fuels has lower performance than traditional JF, however most samples have satisfactory performance and can be used as fuel for aircraft jet engines. It should noted that, some samples have lower values of Net heat of combustion comparing to the standard values in a range 1–2 %, but as this indicator affects the fuel consumption and as a result the amount of exhaust gas from combustion. Since the amount of fluexhaust gases from the AAF is less than the traditional AAF, this value can be neglected.

Calculations of emissions from AAFs blended with bio-additives

For emissions estimation purposes, ICAO has defined a specific reference landing – take-off (LTO) cycle below a height of 915 m (3,000 ft) (Doc 9889, 2011).

This cycle consists of four modal phases chosen to represent approaching, taxiing/idling, take-off and climbing and is a much simplified version of the operational flight cycle (Table 2).

Table 2. Reference LTO cycle of an aircraft (Doc 9889, 2011).

LTO phase	Duration of LTO phase, min	Relative engine thrust, %
Take-off	0.7	100
Climb up to height 915 m	2.2	85
Approach and landing from height 915 m	4.0	30
Taxiing and ground idling	26.0	7

The main aircrafts emissions, which are estimated according to ICAO recommendations are: CO_2, H_2O, SO_2, CH_4, CO, C_xH_y, NO_x and SN (Doc 9889, 2011). The amount of exhaust gas also depends on the type of fuel for the air jet engine, in particular its hydrocarbon and elemental composition (Merkisz *et al.* 2014).

The amount of emissions per one LTO cycle is evaluated in grams of pollutant per cycle for 1 kN of take-off thrust and determined by the formula (when fuel flow is known) (Doc 9889, 2011):

$$M_j = \sum_{i=1}^{4} EI_j \cdot G_i \cdot \tau_i, \qquad (1)$$

where: EI_j – emission index (EI) of pollutant, g/kg of fuel; G_i – fuel flow, kg/s; τ_i – duration of *i* regime, s.

From the formula it is seen that level of emissions depends on the efficiency of combustion chamber that is characterized by EI EI_j and on specific fuel flow G_i at each regime of the LTO cycle (Franchuk, Isaenko 2004).

Taking into consideration typical technical requirements of ICAO to JFs, the quantities of products of complete fuel combustion may be calculated using equations of chemical reaction of burning. The products of complete fuel combustion include CO_2, H_2O, and SO_2. Thus EIs of these compounds can be determined according to equation of chemical reaction of complete oxidation of fuel (complete combustion), which is considered to be stoichiometric (Franchuk, Isaenko, 2004).

The reaction of complete combustion of carbon has the following form:

$$C + O_2 \rightarrow CO_2. \qquad (2)$$

Knowing the coefficients of chemical reaction equation, EI of CO_2 can be calculated as following:

$$EI_{CO_2} = \frac{11}{3} \cdot m_C, \qquad (3)$$

where: m_C – content of carbon in fuel, % (m/m).

Analogously the reaction of complete combustion of hydrogen may be written:

$$2H_2 + O_2 \rightarrow 2H_2O. \qquad (4)$$

Knowing the coefficients of chemical reaction equation, EI of H_2O can be calculated as following:

$$EI_{H_2O} = 9 \cdot m_H, \qquad (5)$$

where: m_H – content of hydrogen in fuel, % (m/m).

Analogously the reaction of complete combustion of sulfur may be written:

$$S + O_2 \rightarrow SO_2. \qquad (6)$$

Knowing the coefficients of chemical reaction equation, EI of SO_2 can be calculated as following:

$$EI_{SO_2} = 2 \cdot m_S. \qquad (7)$$

where: m_S – content of sulfur in fuel, % (m/m).

To calculate emission indices data of hydrogen, carbon and sulfur content in fuel are required. The content of these compounds in the petroleum fuel for the JF is known from literature (Yanovskiy *et al.* 2005). Data on the elemental composition of bio-additives based on rapeseed and camelina oil were calculated basings on chromatographic analysis of its fatty acid composition done during previous studies (Yakovlieva *et al.* 2019).

Table3. Mass ratio of chemical elements in JF and pure bio-additives fuel samples.

Fuel samples	Content, % (m/m)			
	Carbon (C)	Hydrogen (H)	Sulfur (S)	Oxygen (O)
JF of grade Jet A-1	84.975	14.0	0.025	-
FAME of rapeseed oil	77.22	12.01	0.000132	10.77
FAEE of rapeseed oil	77.63	12.13	0.00017	10.24
FAEE of camelina oil	77.99	11.7	0.000168	10.31
FAIBE of camelina oil	78.498	12.01	0.000173	9.49

Table 4. Mass ratio of chemical elements in samples of blended fuels.

Fuel samples	Content, % (m/m)			
	Carbon (C)	Hydrogen (H)	Sulfur (S)	Oxygen (O)
JF of grade Jet A-1	84.975	14	0.025	-
JF+10 % FAME of rapeseed oil	84.2	13.8	0.022513	1.077
JF+20 % FAME of rapeseed oil	83.42	13.6	0.020026	2.154
JF+10 % FAEE of rapeseed oil	84.24	13.81	0.022517	1.02
JF+20 % FAEE of rapeseed oil	83.5	13.63	0.020034	2.05
JF+10 % FAEE of camelina oil	84.28	13.77	0.022517	1.031
JF+20 % FAEE of camelina oil	83.58	13.54	0.020034	2.062
JF+10 % FAIBE of camelina oil	84.33	13.8	0.022517	0.949
JF+20 % FAIBE of camelina oil	83.68	13.6	0.020035	1.898

Therefore, knowing the content in the fuel of total carbon, hydrogen and oxygen, we determine the mass fraction of each component, which corresponds to the composition of FAME, FAEE and FAIBE (Table3).

Knowing the value of the mass ration of chemical elements in pure samples of bio-additives, we calculate the mass fraction of chemical elements in AAF, which contain bio-additives in quantity 10% and 20% (v/v) (Table 4).

Using formulae (3), (5) and (7) EIs of the products of complete fuel combustion CO_2, H_2O, SO_2, were calculated. The calculation was done for conventional JF and samples of blended AAFs, which contained 10% and 20% of each type of studies bio-additives (Fig. 1-3). It was found that combustion of AAFs with bio-additives in quantities 10% and 20% (v/v) results in lower values of CO_2 emissions comparing to combustion of conventional fuel. This may be explained by differences in chemical and element composition of bio-additives and conventional jet fuel. Typical jet fuel contains about 85% of carbon in its composition. At the same time bio-additives contain about 77% of carbon. The similar explanation can be given for H_2O. Plant oil bio-additives naturally have negligible amounts of sulfur. Due to this fact we observe reduction in SO_2 emissions also.

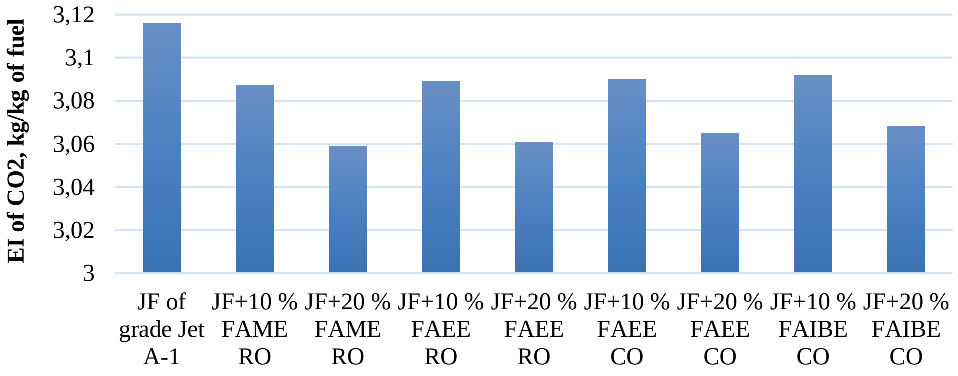

Fig. 1. EI of CO_2 for conventional jet fuel and blended AAFs containing 10% and 20% of bio-additives: RO – rapeseed oil, CO – camelina oil.

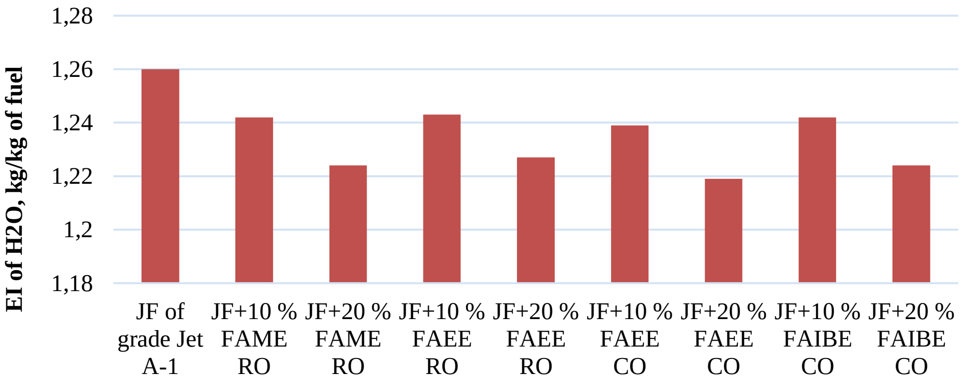

Fig. 2. EI of H_2O for conventional jet fuel and blended AAFs containing 10% and 20% of bio-additives: RO – rapeseed oil, CO – camelina oil.

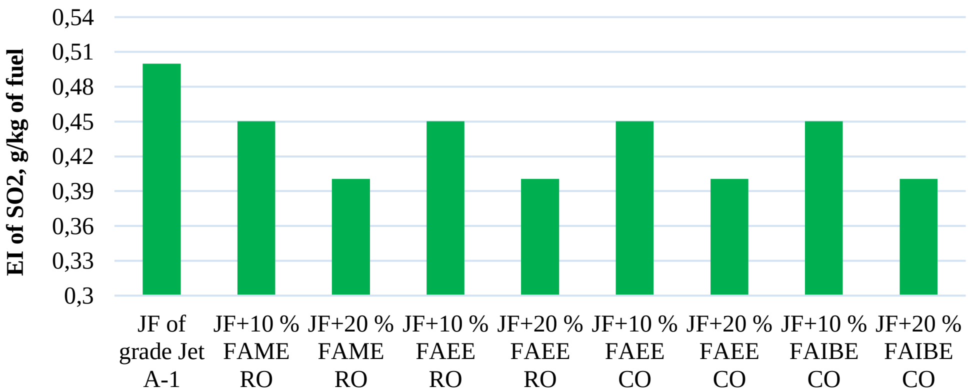

Fig. 3. EI of SO2 for conventional jet fuel and blended AAFs containing 10% and 20% of bio-additives: RO – rapeseed oil, CO – camelina oil.

As it was previously explained emission levels are determined not only by EI of certain pollutant, but also by specific fuel flow at each regime of the LTO cycle and duration of these regimes. Because of that the comparative characteristic of emission levels was developed basing on the total mass of pollutants that is emitted during complete standard LTO cycle (Table 5.). Masses of pollutants were calculated using formula (1). The data about net fuel flow were used from the results of jet engine operation parameters testing. Standard duration time of LTO cycle regimes was taken as it is recommended by ICAO.

Table 5. Characteristics of aircraft exhaust gases.

Fuel Samples	Characteristics of aircraft exhaust gases – mass of pollutant, kg/standard TLO cycle					
	CO_2	Change of parameters, %	H_2O	Change of parameters, %	SO_2	Change of parameters, %
JF of grade Jet A-1	573.87	-	232.05	-	0.092	-
JF+10% FAEE rapeseed oil	496.26	-13.52	199.69	-13.95	0.072	-21.85
JF+20% FAEE rapeseed oil	509.77	-11.17	204.34	-11.94	0.067	-27.61
JF+10% FAME rapeseed oil	499.60	-12.94	201.01	-13.38	0.073	-20.87
JF+20% FAME rapeseed oil	508.82	-11.34	203.59	-12.27	0.067	-27.72
JF+10% FAEE camelina oil	497.85	-13.25	199.62	-13.25	0.072	-21.3
JF+20% FAEE camelina oil	507.58	-11.55	201.87	-11.55	0.066	-28.04
JF+10% FAIBE camelina oil	498.45	-13.14	200.21	-13.14	0.073	-21.2
JF+20% FAIBE camelina oil	508.0	-11.48	202.67	-12.67	0.066	-28.04

Basing on the results of analysis we can make the conclusion that blending conventional JFs with bio-additives in quantity up to 20% (v/v) allows decreasing total level of exhaust gases emissions form aircraft jet engines. The obtained results allowed us concluding that aircraft's emission level is a complex characteristic that depends on both type of JF used (it quality, element and hydrocarbon composition) and jet engine operation parameters (efficiency of combustion process, fuel flaw).

Conclusions

This of products of complete JF combustion – CO_2, H_2O and SO_2 – may be predicted (calculated) basing on data about fuel's chemical and element composition and do not require fulfilling jet engine's bench test. The results have shown that increasing ratio of bio-additive in JF blends causes corresponded decreasing of studied pollutants EIs. Adding 20% (v/v) of bio-additives may results in decreasing CO_2 EI up to 1.83%, H_2O EI up to 3.25%, and SO_2 EI up to 20%.

At the same time evaluation of total mass of pollutants emitted during standard LTO cycle has shown different results. Blending conventional JFs with bio-additives generally decreases the total mass of emissions. However, adding 10% (v/v) of bio-additives allows reaching more reduction of mass of emissions than in case when 20% (v/v) of bio-additive is added to conventional JF. This result is explained by that fact that fuel flow was higher for JF blend containing 20% of bio-additives (especially at idling and 0.8 of nominal regimes of jet engine operation). Thus, finally we can make the conclusion that adding 10% (v/v) of any bio-additive will be effective for exhaust gases reduction. However, the rapeseed oil FAEE and camelina IBFAEE bio-additives may results in decreasing mass of CO_2 emissions up to 13.52%, mass of H_2O emissions up to 13.95% and mass of SO_2 emissions up to 21.85%, and seems to be the most effective.

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