

REDUCTION EMISSION LEVEL OF HARMFUL COMPONENTS EXHAUST GASES BY MEANS OF CONTROL OF PARAMETERS INFLUENCING ON SPRAYING PROCESS OF BIOFUEL COMPONENTS FOR AIRCRAFT ENGINES

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Abstract

The aim of the research is to test the fuel additives which decrease dimensions of atomised fuel drops, by applying changes to the specific parameters which impact the atomisation process. Those parameters include density, surface tension, viscosity and the viscosity index. Dimensions of drops of biofuels are much bigger compared to hydrocarbon fuels. By modifying the physical and chemical parameters of biofuels, dimensions of drops in an atomised fuel stream should become smaller. Those dimensions play a major role for the level of emissions of hydrocarbon and carbon monoxide, as well as mainly nitrogen oxides and particulates. The research on emissions of toxic components of fuel is relatively advanced today in the field of piston combustion engines, especially for use in car vehicles. However, the dynamic development of the air transport brings more pressure on the issue of toxic emissions in the case of aircraft engines. The level of toxic emissions from aircraft engines may be from ten up to even several thousand times greater than the level of emissions from piston engines. The issue of how biofuel additives can affect the process of fuel atomisation and thus enable the control over the atomisation to obtain the smallest possible drops leading to reduced nitrogen oxides emissions is a new and original issue. The reduced nitrogen oxides emissions in the case of biofuels is of utmost significance because, according to latest knowledge, those levels are increasing.

Keywords: *transport, aircraft engines, alternative fuels, fuel atomization, exhaust gas emissions*

1. Introduction

Chemical structure of bio-hydrocarbons, added to aviation engine fuels, have capital influence on the reduction of harmful fuel emissions, in particular the emission of nitrogen oxides. Fuel additives should reduce dimensions of drops of atomised fuel in view of the fact that the dimensions are significantly larger in the case of biofuels compared to hydrocarbon fuels. Those dimensions play a major role for the level of emissions of hydrocarbons and carbon monoxide, as well as nitrogen oxides and particulate matter [2-9].

Key affair consists in modified physical and chemical properties of fuels, leading to smaller dimensions of drops of atomised fuel and decreased level of emissions, and nitrogen oxides in particular. The research into emissions of toxic components of exhaust gases are relatively advanced today in the field of piston combustion engines, especially for use in motor vehicles. The dynamic development of the air transport brings more pressure on the issue of toxic fuel emissions related to aircraft engines. In Poland, that issue has not been researched on a wider scale almost at all, save for the efforts to define the current status – and it is alarming. The level of toxic emissions from aircraft engines may be from ten up to several thousand times greater than the level of emissions from piston engines. That fact makes it necessary to research the situation of the aircraft engines.

2 Biofuels

Biofuels are characterised by reduced emissions of carbon monoxide and hydrocarbons, but higher emissions of nitrogen oxides. The increased nitrogen oxides emission is a significant issue

for the protection of the environment because nitrogen oxides are among the most toxic components of exhaust gases. Research results show that the quality of the exhaust gases depends much on the atomisation of fuel. It is so because two-phase fuel mixtures are combusted with the slowest physical processes. One of those slowest processes is evaporation. The speed of evaporation of liquid drops is directly proportional to the quality of atomisation. In Poland, scientific research on that issue covered only the analysis and tests of the toxic emissions processes for piston combustion engines, intended mainly for motor vehicles. No efforts have been taken to cover turbine jet engines.

3. Basics of problem

The issue of how biofuel additives can affect the process of fuel atomisation and thus enable the control over the atomisation to obtain the smallest possible drops leading to reduced nitrogen oxides emissions is a new and original issue. The reduced nitrogen oxides emission in the case of biofuels is of utmost significance because, according to latest knowledge, those levels are increasing. Regardless of the other benefits of biofuels, such effect is highly disadvantageous especially considering the fact that nitrogen oxides are extremely toxic for the environment. Although research on effects of fuel atomisation is ongoing across various scientific centres, the issue of control over the atomisation of biofuels using dedicated additives in order to reduce nitrogen oxides emissions has not been studied yet. The research on the atomisation of drops is in progress at, among other facilities: Berkeley University, University of Wisconsin-Madison, Wayne State University, Ford Research Laboratory, Center for Turbulence Research, Perdue University, (USA), Chalmers University of Technology (Sweden), Karlsruhe University (Germany), Prague University (Czech Republic). The research initiatives concern mainly methods to obtain smaller drops in order to increase the atomisation of fuel and create a fuel stream where drops will not hit the combustion chamber. For example, according to the research at Karlsruhe University, large drops of fuel caused high hydrocarbon emissions [1], [9], [10]. In many combustion systems, streams of small drops are injected into the combustion chamber. In compression-ignition engines, small drops of fuel determine the speed of combustion by reducing the ignition lag. In the aforementioned scientific centres, special attention is paid to the fact that larger drops of fuel are much more harmful for the combustion process because of insufficient time for the evaporation phase. A large portion of research concerns effects of the atomisation of fuel on “cold” engine start. Small drops of atomised fuel are required for effective ignition and correct combustion during a “cold” engine start, as well as for the reduced hydrocarbon emissions. For example, according to the research at ORBITAL, very small drops of fuel combined with a small penetration of the fuel stream (based on air-supported atomisation) have a good effect on the combustion process: improved stability of the process itself, reduced fuel consumption, and reduced hydrocarbon emission.

Particulates are created during the combustion process because molecules with carbon condensate to solid particulate matter. Particulates are caustic, toxic and hazardous for human beings. Particulates can be categorised into two classes: PM and PM10. PM10 is a more important problem because it can penetrate the body of humans and animals. By principle, the lower level of particulate emissions the higher the level of nitrogen oxides emissions. However, the improved process of atomisation based on smaller drops of fuel gives a positive effect on the combustion leading to the reduced levels of particulates. The dimensions of atomised drops of fuel play a major role also in the emission of particulates. Large drops cause higher emissions of particulates not only due to their prolonged combustion and the low local excess air factor, but also because of the settlement of particulates on walls of the combustion chamber. Fuel “spills” on the walls contribute greatly to higher emissions of particulates, and such “spills” occur when the drops are larger. Streams of small-drop fuel do not show such properties. To counteract the higher nitrogen

oxides emission, it is recommended to greatly reduce the average size of a fuel drop. Thanks to that, fuel molecules spend less time in the reaction zone. Also, good effects on reduced carbon monoxide emissions are possible thanks to turbulisation of fuel in the combustion chamber and multi-injection systems in piston engines.

Nitrogen oxides are among the most hazardous chemical compounds found in the exhaust gases. On the one hand, nitrogen oxides are responsible for photochemical smog and on the other hand - for acid rain which poisons a great share of the Earth. Nitrogen oxides are very durable compounds that travel long distances to cause harm in remote locations far from the place of origin. Although motor vehicles remain among the greatest sources of nitrogen oxides, the development of air transport necessitates scientific research of issues related to the aircraft engines, with results applicable to motor vehicle and other engines, as well. The most frequent nitrogen oxides include nitrogen oxide (NO) and nitrogen dioxide (NO₂), jointly referred to as nitrogen oxides (NO_x). There is also nitrous oxide (N₂O). There are three mechanisms for creating nitrogen oxides: thermal, prompt and fuel processes. The thermal mechanism, or the so-called Zeldovich mechanism, is the basic mechanism for creating NO in internal combustion engines. In that mechanism, the process starts with the thermal dissociation of oxygen and nitrogen molecules. The high energy involved in their bonds, especially in the case of nitrogen molecules, makes the creation of NO possible in high temperatures only, according to that mechanism. The speed to create NO depends highly on the temperature and less on the oxygen content. Thus, the combustion process should occur with insufficient oxygen content during the high temperature phase, and oxygen should be in excess when the temperature is low during the afterburning phase. Such process is applied in the two-phase combustion systems.

Hydrocarbon fuels combusted in temperatures below 1000°C could lead to relatively higher content of nitrogen oxide than assumed in the thermal mechanism. In that case, the prompt mechanism takes place. The prompt creation of nitrogen oxides is faster by one order of magnitude than in the case of the Zeldovich thermal mechanism which is based on equivalent concentration of radicals. There are three causes of prompt creation of NO during the combustion of hydrocarbon fuels: non-equivalent concentration of O and OH radicals in the reaction zone and the exhaust gases which accelerate the thermal mechanism of creation of NO; reactions started by hydrocarbon radicals present in the reaction zone with nitrogen molecules (so called Fenimore mechanism); reaction of oxygen atoms with N₂ leading to the creation N₂O based on trimolecular recombination. The accelerated creation of NO caused by non-equivalent concentration of radicals appears to be the key factor in the case of uniform (non-mixed) flames and lean mixtures. The prompt creation of NO based on the reactions of hydrocarbon radicals and molecular nitrogen prevails in the case of combustion of rich hydrocarbon mixtures in diffusion flames. The prompt creation of NO based on the N₂O mechanism plays a major role when there is less fuel than air, smaller combustion temperature or higher pressure. The N₂O mechanism prevails when the speed to create NO is relatively slow.

The third mechanism is the fuel mechanism. Nitrogen oxides are created based on indirect transformation of nitrogen bonded in fuel. Nitrogen comes from the nitrogen compounds present in liquid fossil fuels, resulting mainly from protein decomposition processes. In the combustion zone, nitrogen compounds found in fuel are decomposed into nitric compounds which are then transformed into radicals with nitrogen atoms. The radicals react quickly with substrates containing oxygen. The transformation of nitrogen in fuels into nitrogen oxides depends greatly on the excess air factor and the combustion temperature, rather than the structure of the compounds. The creation of NO based on nitrogen in fuel requires much less energy than in the case of the Zeldovich mechanism. It should be emphasised that, among all the NO_x mechanisms, the thermal one plays the key role in the case of engines.

An accelerated combustion process does not necessarily lead to reduced nitrogen oxides emissions because of the specifics of the thermal creation of the nitrogen oxides. In view of the

thermal mechanism, the level of nitrogen oxides emissions depends on the temperature. However, another important factor for the nitrogen oxides emissions – and the start point for the proposed research – is the time which a fuel molecule spends in the reaction zone. That time depends mainly on the size of fuel drops. The time for a fuel molecule to spend in the reaction zone is of prime importance, and the proposed research takes that into account. With small drops of fuel, the time in the reaction zone can play a dominant role for the level of nitrogen oxides emissions. It is true within a specific temperature range and for low overall emissions. The level of nitrogen oxides emissions depends on the maximum temperature of the flame, the local concentration of nitrogen and oxygen molecules, and the time spent in the high-temperature zone. Thus, the small dimensions of fuel drops and strong turbulence could lead to reduced nitrogen oxides emissions. In the recent times, intensive research efforts have been taken to ensure reduced NO_x emissions using high-temperature combustion and intensive turbulisation, further justifying the above-mentioned standpoints. A high-temperature combustion process uses high temperature to reduce the nitrogen oxides emissions based on the reversed Zeldovich mechanism. The time which a molecule spends in the combustion zone is highly significant. The below figure shows the effect of SMD drops in a stream on NO emission vs. the equivalence ratio (Φ) for an internal combustion engine.

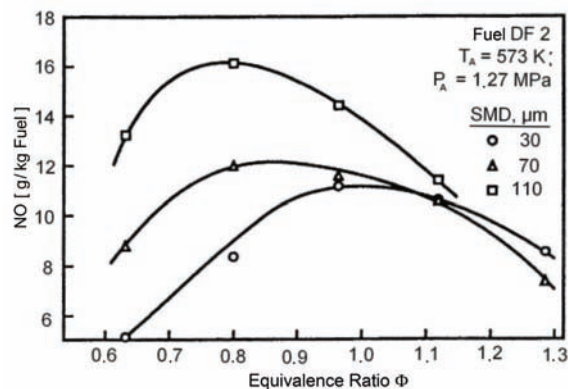


Fig. 1. Influence of drop dimensions on the NO emission level

NO emissions depend highly on Φ . With a lean mixture of $\Phi < 1$ most emissions are generated when SMD is high. With a rich mixture, NO emissions depend very little on the size of drops. It is caused by diffusive combustion of large drops with a local fuel-to-air proportion close to the stoichiometric ratio. High temperature is created locally leading to high NO content. A decreased diameter of drops hinders that process causing the combustion process to occur mostly with a uniform mixture which has a slower speed of NO creation. Even in the case of very low equivalence ratio (lean mixture) with low average temperature, large drops in the combustion zone create conditions in which the mixture is almost stoichiometric causing high NO content.

5. Research Methodology

In order to develop the operating algorithm enabling the control over the physical and chemical properties of JET-type fuels, a series of fuel mixes will be prepared, each with different additive setup. Laser technology tests will be carried out using LDV (Laser Doppler Velocimeter) and PDPA (Phase Doppler Particle Analyzer). All test results will be measured in a dedicated measurement zone defined by the crossing of two laser beams: zero beam and Doppler beam. The measurement zone is within the optical focus of the laser transmitter, in the form of a rhomboid solid. The measurement zone dimensions can be changed using the optical system of the transmitter which is adjusted to the projected range of diameters of drops appearing in the atomised fuel stream. The measurable size of drops is within the range from 0.1 μm to 2.5 mm. The measurement range depends on the optical system and the RSA processor (Real Time Signal Analyzer). In any event, the optical system should be configured as follows: the maximum

dimension of a drop should be less than the shorter diagonal in the cross-section of a rhomb which is perpendicular to the velocity vector of the fuel stream, and the minimum measurable dimension of a drop should be $0.1 \mu\text{m}$. The LDV system for measuring velocity does not require calibration. The velocity component is measured based on the recorded changes of frequency of the Doppler laser beam, with the frequency being proportional to the velocity of the fuel drop. The PDPA system for measuring dimensions of drops requires electronic calibration, i.e. certain electronic parameters must be adjusted to the projected measurement range of the diameters of drops appearing in the measurement zone. The dimensions of drops are measured based on the recorded deflection of the laser beam when passing through a drop, with the deflection being proportional to the dimension of the drop. Prior to calibration, the measurement system must be centred, with special attention paid to the equal power of both laser beams: the zero beam and the Doppler beam, in all directions in the skewed co-ordinate system. View of LDV-PDPA laser system with research chamber presents Fig. 2.



Fig. 2. View of LDV-PDPA laser system with research chamber

The exact location where a stream is integral and starts disintegrating can be defined by experimenting based on measurements of the diameter and velocity of drops, using LDV and PDPA. Where the stream is integral, the laser measurements cannot be realised. In order to define the location where the stream disintegrates, the measurement zone is moved from the atomiser nozzle along the path of the stream. In LDV and PDPA, measurements are taken within the focus of the laser transmitter. The stream is considered disintegrated at the location where the diameter and velocity of a large number of drops can be measured effectively, with repeated results in consequential trials. During the calibration, optical parameters were set for the defined range of drops in order to ensure that dimensions of the drops in the stream are measured. Using the optical system of the laser transmitter, the system can be adjusted to correspond to the occurring range of drops. The location where the fuel stream disintegrates depends on the pressure at the nozzle and the properties of fuel, i.e. mainly its density, viscosity, and surface tension. In order to enable comparable test results, the measurement spots are set in distances assuming even the longest path of disintegration of the stream. When selecting the measurement spots, other related aspects are considered, as well, such as visible drops near the ignition plug related to the fuel injection, and the diameter of drops near walls of the cylinder. As regards the evaluation of the engine fuel feed system, it is recommended to measure the Sauter mean diameter at $2/3$ of the stream length from the nozzle and $2/3$ of the stream width from the centre axis.

4. Conclusions

Upon an analysis of the current knowledge in the area of biofuels, the key to lower the emissions of e.g. nitrogen oxides appears to be the control over the atomisation of fuel.

In terms of the properties of fuel, the atomisation process depends greatly on: viscosity, surface tension and density, as well as the viscosity index, heat of evaporation and the specific heat.

Those factors affect the dimensions of atomised fuel drops and the properties of the fuel stream. The impact of those factors also extends to the level of toxic emissions, in particular nitrogen oxides, as those are related mainly with the average size of fuel drops. Those properties could also provide an explanation for the issue of increased nitrogen oxides emissions in case of e.g. alternative rape-seed oil fuel which features higher viscosity and density compared to diesel oil. Initial research shows that the atomisation of biofuels results in larger dimensions of fuel drops leading to increased nitrogen oxides emissions, with nitrogen oxides being the most toxic component in exhaust gases.

Oxygen content in biofuels enables reduced emission of non-combusted hydrocarbons and carbon monoxide. Still the reduced size of atomised fuel drops can lead to even greater reduction of emissions of hydrocarbons, carbon monoxide and, last but not least, nitrogen oxides.

By modifying physical and chemical properties of fuel using selected additives (e.g. bio-hydrocarbons), certain physical and chemical properties can be altered, such as the surface tension, viscosity and the viscosity index, and density of fuel. The fuel atomisation process will be diversified by controlling the fuel properties, leading to changes in emissions.

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