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Paweł NISZCZOTA[1] ORCID 0000-0002-1370-3528,
pawel.niszczota@itwl.pl – corresponding author
Marian GIERAS[2] ORCID 0000-0002-0219-561X, marian.gieras@pw.edu.pl
[1] Air Force Institute of Technology (Instytut Techniczny Wojsk Lotniczych), Poland
[2] Warsaw University of Technology (Politechnika Warszawska), Poland

INFLUENCE OF SURFACTANT ADDITION TO EMULSION FUELS ON THE HOT SECTION OF TURBINE ENGINES

Wpływ dodatku środka powierzchniowo-czynnego do paliw emulsyjnych na gorącą sekcję silników

Abstract: *Due to the growing awareness of ecological threats, more and more attention is paid to the emission problem of undesirable substances into the atmosphere, the source of which is transport and energy. The impact of these factors on the environment can be reduced by using alternative fuels, which are non-fossil fuels, or by modifying these fuels to ensure lower emissions. One of the methods for reducing emissions from engines is the use of water fuel emulsion as fuel, which has a particularly positive effect on the emission of nitrogen oxides at high loads of drive and power units. An important issue affecting the possibility of using this fuel type is the impact of their use on the elements of the units in contact with fuel containing water and, optionally, an emulsifier. This paper presents inspection results of the hot section of a miniature gas turbine powered by Jet-A1 aviation fuel with the emulsifier addition. On the basis of these observations, the components of emulsion fuels were determined, which are the cause of the characteristic deposits occurring on the hot sections of the units after using emulsion fuels.*
Keywords: engine hot section, alternative fuels, surfactant, emulsifier, emulsion fuels, fuel-water emulsion

Streszczenie: *Ze względu na rosnącą świadomość zagrożeń ekologicznych przykłada się coraz większą wagę do problemu emisji do atmosfery substancji niepożądanych, których źródłem jest transport i energetyka. Jedną z dróg prowadzących do zmniejszenia wpływu tych czynników na środowisko jest wykorzystanie paliw alternatywnych, będących paliwami niekopalnymi, bądź modyfikacja tych paliw zapewniająca mniejszą emisję. Jedną z metod obniżenia emisji z silników jest zastosowanie, jako paliwa, emulsji paliwowo-wodnej, która* *wpływa szczególnie pozytywnie na emisję tlenków azotu przy dużych obciążeniach jednostek napędowych i energetycznych. Ważną kwestią wpływającą na możliwość zastosowania tego typu paliw jest wpływ ich stosowania na elementy jednostek będące w kontakcie z paliwem zawierającym wodę oraz opcjonalnie emulgator. W niniejszej pracy zostały przedstawione wyniki inspekcji gorącej sekcji miniaturowej turbiny gazowej, która była zasilana paliwem lotniczym Jet-A1 z dodatkiem emulgatora. Na podstawie tych obserwacji określono składniki paliw emulsyjnych będących przyczyną występowania charakterystycznych osadów występujących na gorących sekcjach jednostek po zastosowaniu paliw emulsyjnych.*

Słowa kluczowe: gorąca sekcja silnika, paliwa alternatywne, środek powierzchniowo-czynny, emulgator, paliwa emulsyjne, emulsja paliwowo-wodna

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1. Introduction

The water-fuel emulsion used in combustion is a mixture of at least two liquids, one of which is a hydrocarbon fuel, e.g. diesel, biodiesel or Jet-A, and the other is water. The most commonly used type of emulsion is the water-in-oil type. It is an emulsion whose continuous phase is fuel, and water is trapped in the form of microscopic or ultra-microscopic droplets in the continuous phase, constituting the discrete phase of the emulsion [1-3].

The fuel-water emulsion is made with or without emulsifiers. Emulsions that are prepared without the use of surfactants are usually prepared in purpose-built homogenizers constituting an element of the fuel system, in which the components of the target fuel mixture are intensively mixed just before its injection into the combustion chamber [4,5]. On the other hand, the emulsion containing the emulsifier can be prepared before placing the fuel mixture in the fuel tank in a separate technological process. This is because the addition of an emulsifier reduces the thermodynamic instability of the emulsion, and the surface tension between the liquids as well as limits the increase of the interfacial free energy, which contributes to an increase in the emulsion stability [6,7].

Water-fuel emulsion is a functional fuel for internal combustion engines [1, 8]. Its combustion was tested on a full-size power gas turbine Alsthom 9000B [9]. The Simens company successfully modified the combustion chambers of the V94.V3 and V84.V3 turbines, enabling them to work effectively on emulsion fuel as one of the options [10, 11]. The General Electric company conducted tests with positive results on the MS5002E gas turbine combustion chamber test bench, combustion of emulsion fuel with a water/fuel ratio exceeding 1 [12]. An experiment was carried out in Greece, for the implementation of which four public transport buses were used, which were powered by emulsion fuel during the journey according to the normal timetable. During the tests, the vehicles travelled a total of over 12,000 km, burning diesel with 13% by volume of water. The tests showed a positive effect of the use of the emulsion on the emission and consumption of the base fuel. In the conclusions, the use of a fuel-water emulsion instead of pure diesel as fuel for a city bus was defined as an attractive alternative [13]. In [14], the results of research conducted on a four-stroke diesel engine with direct injection are described. The emulsions used in the experiment contained from 13% to 17% of water. After completing the 500-hour test, no engine problems or damage were identified.

Combustion of the fuel-water emulsion during long-term operation of the engine with the use of an emulsifier is usually less economical than combustion of the emulsion produced in the fuel system by means of a homogenizer. This is because the cost of a kilogram of emulsifier is about an order of magnitude higher than the cost of the base fuel, on the example of a mixture with the composition described in [15]. The typical emulsifier content in the mixture in most of the tested cases oscillates around 2% [2]. In the paper mentioned earlier [9], the possibility of reducing emissions from an industrial gas turbine by using emulsion fuel with the addition of an emulsifier to the mixture was investigated, assuming that for economic reasons its concentration in the emulsion cannot exceed 100ppm.

Despite the increase in costs, the combustion of the emulsion containing the emulsifier may be beneficial in terms of time and money in short-term tests where the cost of the emulsifier used is lower than the cost of modifying the fuel system or in cases where durability of the fuel mixture is required. And the production of a fuel emulsion with the use of an emulsifier is a technologically uncomplicated and not very time-consuming process [15, 16].

The emulsifier added to the fuel may affect the emulsion combustion process. In the tests on single emulsion drops, a separate stage of the droplet evaporation and combustion process is observed, which is the combustion of the emulsifier [17,18]. On the other hand, the review article [2], focusing on the combustion of emulsion fuel in piston engines, emphasizes the research gap in the knowledge on the impact of combustion of various types of emulsifiers on engine performance and emissions. In the miniature gas turbine GTM-120, a study was carried out to check the effect of emulsifier addition to fuel in the amount of 2% and 5% (by weight) of the total fuel mixture on operating parameters and emissions [19]. It has been shown that it has a statistically significant effect on the combustion process. However, in the context of tests conducted on the same gas turbine [20, 21], where an emulsion containing 2% of emulsifier and 3% of water was burned, the effect of water addition on emission is dominant from its smallest tested content.

In the context of the above comments, it seems reasonable to conduct scientific research or industrial exploratory research with the use of a fuel-water emulsion produced with the use of an emulsifier. However, previous publications contain only fragmentary information on the effect of the emulsifier and water contained in the emulsion on the hot section of engines, although the need for such research is emphasized by scientists [1, 22]. One of the few mentions of this issue can be found in [23], where it is stated that after a series of tests on the walls of the combustion chamber, "varnish-type" contamination was observed, which was attributed to emulsifier, but it should be noted that in these studies, the emulsifier content reached 20% of the emulsion volume, which significantly exceeds the common share. However, in [14], despite the fact that during the inspection there was no damage to the unit due to using emulsion as fuel, the presence of a deposit resembling white dust was found in the vicinity of the inlet valve. This effect was attributed to the combustion of the emulsifier contained in the emulsion (the proportion of the emulsifier was not specified). In both of the above-mentioned cases, the photographic documentation of the observed sediments is of little use due to the quality of the photographs.

Due to the indications that the emulsifier contained in the fuel mixture may leave deposits on the hot part of the engine, and after a series of tests using a miniature turbine engine in which fuel with the addition of emulsifier was combusted, an inspection of the hot section of the engine was carried out by the authors and its results are the subject of this publication.

2. Test stand and test procedure

2.1. Test stand

The research object was a miniature GTM120 gas turbine manufactured by JetPol from Poznań. It is an engine with a single-stage radial compressor coupled to a single-stage turbine and a combustion chamber based on quasi-reversible flow. The combustion chamber of this unit is equipped with evaporators that enable the atomization of the injected fuel stream and the heating and evaporation of the resulting liquid droplets (Fig. 1). In Fig. 1 combustion chamber walls are marked in yellow and 12 evaporators are marked in blue. Most of the air enters the combustion chamber through the holes in the liner (approx. 94.5%,for rotations of 120 kPRM), while the remaining part flows to the end of the external annular channel of the engine and enters the evaporator pipes to the primary combustion zone [24].

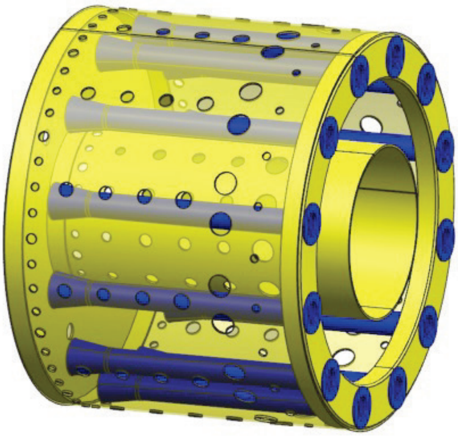


Fig. 1. CAD model of the combustion chamber of the GTM120 turbine engine

The GTM120 engine is characterized by a thrust of 120N, fuel consumption at a maximum load of about 7 g/s with air flow in the intake of about 0.35 kg/s. For these operating parameters, the temperature behind the combustion chamber exceeds 950K [25]. The feature that distinguishes this unit from the newer versions of the GTM series engines is that the engine start-up is initiated with gaseous fuel (e.g. propane-butane), and the liquid fuel is fed only after reaching temperatures inside the combustion chamber that allow its evaporation. Apart from the start-up phase, the turbine operates only on liquid fuel, which is JET-A1 with an admixture of oil up to 5% (Aeroshell 500). This admixture is responsible for the lubrication of the engine bearings, which is carried out in an open system with 2.5% of the combustible mixture discharged from the fuel system before being injected into the combustion chamber.

During the experimental tests, the GTM120 gas turbine was placed on a platform enabling the engine to move in the direction consistent with the longitudinal axis of the engine, thanks to which thrust measurement is possible (Fig. 2a). The gaseous fuel used during the start-up was commercially available propane-butane (Fig. 2b). The moment of cutting off the supply of gaseous fuel is carried out automatically by the engine controller by means of a solenoid valve. Standard and modified liquid fuel was fed from the fuel tank (Fig 2c) and pumped to the engine by a voltage-controlled gear pump. A fuel filter was placed in front of the fuel pump, and the moment of starting the fuel supply to the combustion chamber and its cut-off was controlled by a solenoid valve. The fuel pump, solenoid valves and engine controller were located on the underside of the movable part of the platform to which the engine was attached.

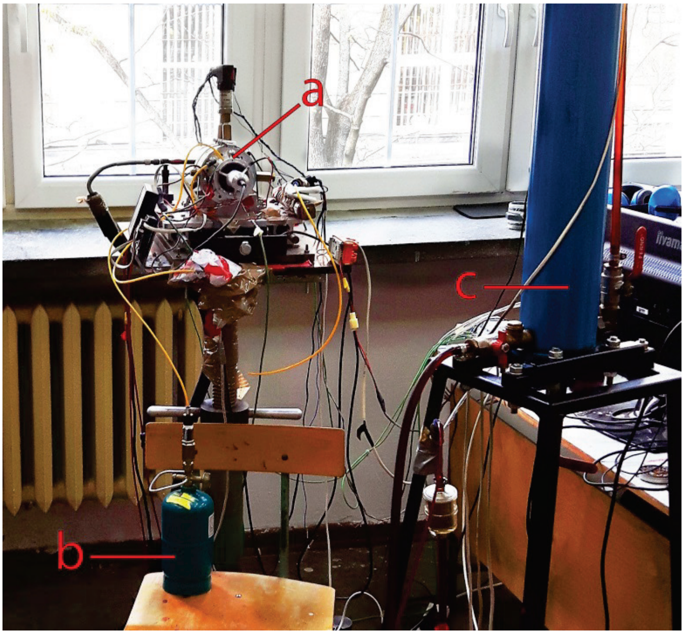


Fig. 2. GTM120 gas turbine test stand: (**a**) GTM120; (**b**) gas fuel tank; (**c**) liquide fuel tank

2.2. Research procedure

During all experiments, the results of which are presented in this publication, the GTM120 gas turbine was powered by fuels with three different proportions of components; i.e., standard fuel recommended by the manufacturer and two fuels mixed with a surfactant. The composition of the fuel mixtures used is shown in Table 1. The standard fuel (M1) was alternately combusted with the modified fuels M2 and M3.

Table 1

Percentage of ingredients in the fuel mixture (by weight)

Fuel Mixture	Jet A-1	Oil	Surfactant
M1	95.00	5.00	0.00
M2	93.10	4.90	2.00
M3	90.25	4.75	5.00

The surfactant used in the tests was a mixture of four surfactants produced by PCC SE and demineralized water (Table 2).

Table 2

Percentage of ingredients in the fuel mixture (by weight)

Surfactant Ingredients	Procentage
Rokwin 80	50.00
Rokanol RZ4P11	25.00
Rokanol DB3	22.50
Rokafenol N8	1.67
Water	0.83

All experimental studies were carried out in ambient conditions with a pressure in the range of 982 – 1015 hPa and an ambient temperature of 16.3°C to 24.7°C. During research, 14 tests were carried out with the use of M1 fuel, 10 tests during which M2 fuel was burned and 9 tests with M3 fuel. The course of each experimental trial was unchanged regardless of the fuel type which powered the GTM120 turbine. The course of the experimental trial can be divided into 7 stages (Fig. 3). The initial phase was the start-up, during which the fuel was ignited, the transition from gas fuel combustion to liquid fuel combustion and reaching the speed of 40 kRPM (Fig. 3, I). After the start-up, the turbine operated for 90 seconds at 40 kRPM. After 90 s, the speed was increased by 20 kRPM (Fig. 3, II), and this procedure was repeated until the engine speed reached 120 kRPM (Fig. 3, VI). The last stage of the experimental test was to reduce the revolutions to 80 kRPM and maintain them for about 10 seconds, after which the fuel supply was cut off.

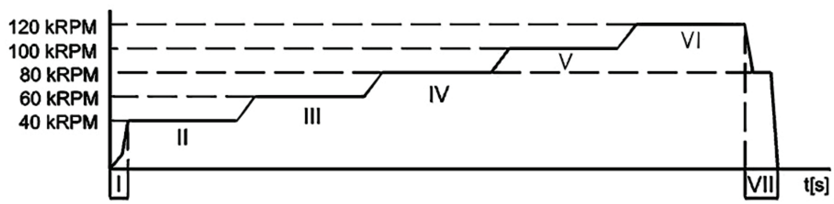


Fig. 3. Scheme of the course of the experimental test

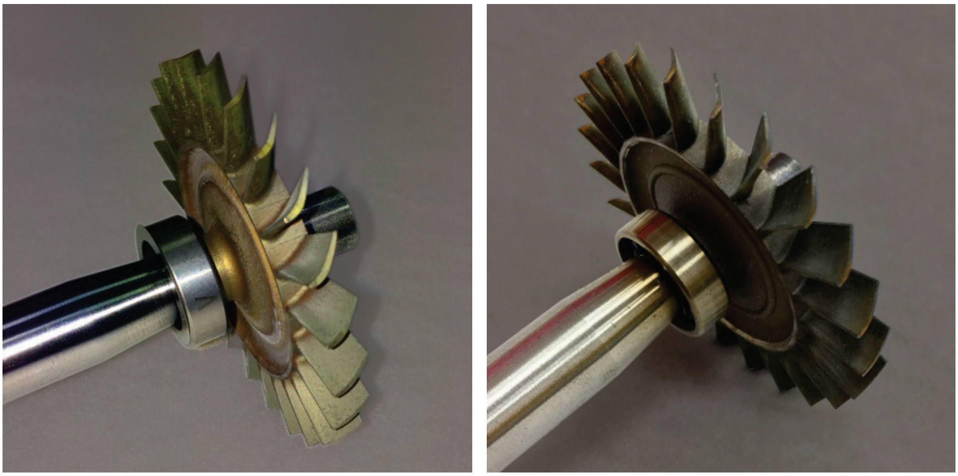
After completing the series of experiments described above, the engine was disassembled in order to inspect the hot section of the engine and obtain photographic documentation.

This chapter should include the applied methodology, research procedures, applied materials and instruments.

3. Results

This chapter presents the photographic documentation of the hot section of the GTM120 turbine after a series of tests in which alternative fuel was burned, comparing it with the hot section of the turbine, in which alternative fuels were never used. The elements of the GTM160 engine, manufactured by the same company and identical in principle to the course of the combustion process, were used for comparison.

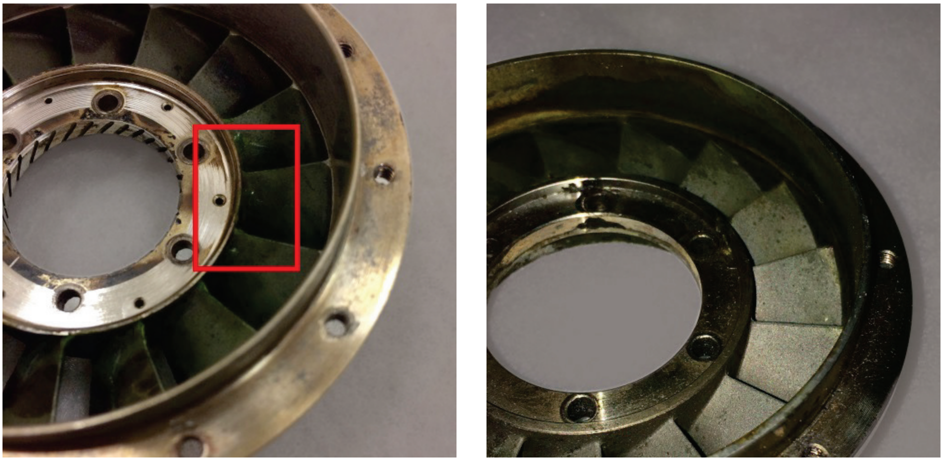
As a result of the combustion of fuel with the addition of emulsifier, a clearly visible green coating appeared on the turbine blades, in particular on the upper surface of the profile (Fig. 4a). On the blades of the turbine that did not work with fuel containing surfactants, no such deposit was noted (Fig. 4b). The visible, orange coating on the blades of the turbine of the GTM160 engine shown in the photo (Fig4b) is ordinary corrosion, not directly related to the fuel used for combustion.



(**a**) (**b**)

Fig. 4. Turbine of the engine in which fuel was burned: (**a**) with added emulsifier; (**b**) without added emulsifier

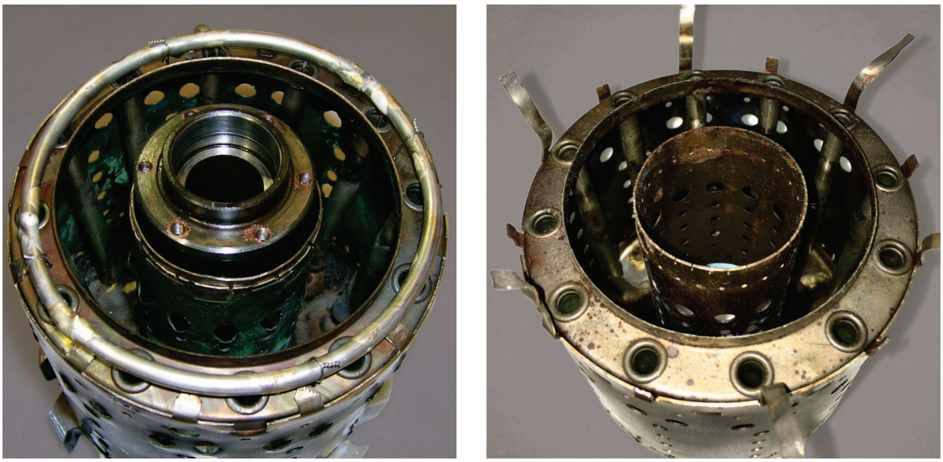
Even more easily noticeable effects of fuel combustion with emulsifier than on the turbine rotor blades occurred on the turbine stator blades. In addition to the green coating on the blades of the turbine stator, green, glassy deposits appeared in the area of the base of the blades (Fig. 5a). Similar deposits were not observed on the comparative element from the GTM160 engine (Fig 5b).



(**a**) (**b**)

Fig. 5. Turbine stator blades of an engine in which fuel was burnt: (**a**) with added emulsifier; (**b**) without added emulsifier

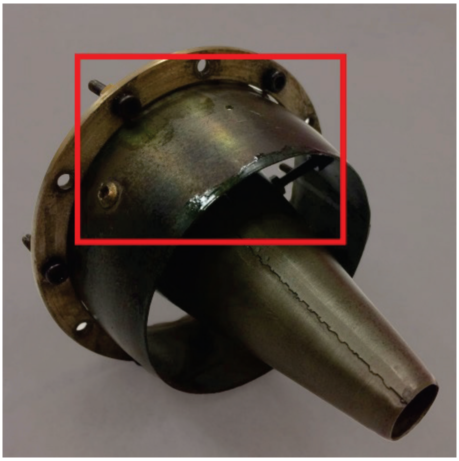
Combustion of fuel with an admixture of emulsifier caused the appearance of a green coating also on the walls of the combustion chamber and the walls of the evaporators (Fig. 6a). This effect is very clear. No unusual discolorations were noted on the walls of the combustion chamber of the engine that ran on fuel without the addition of emulsifier (Fig. 6b).



(**a**) (**b**)

Fig. 6. Combustion chamber with evaporators of the engine in which the fuel was burned: (**a**) with added emulsifier; (**b**) without added emulsifier.

Green glassy deposits were also observed on the engine exhaust nozzle after a series of tests with fuel combustion with the addition of an emulsifier (Fig. 7a). They occurred on the part of the nozzle which was directed downwards during the tests. This was probably due to the fuel, which insignificant amounts accumulated in this area after a failed engine start-up and after increasing the temperature of the exhaust nozzle during the next experimental test, they formed a characteristic deposit. No deposits occurred on the nozzle of the engine which was operated in a similar way, but no emulsifier was added to the fuel it burned (Fig 7b).



(**a**)

(**b**)

Fig. 7. Exhaust nozzle of the engine in which the fuel was burned: (**a**) with added emulsifier; (**b**) without added emulsifier

During the research, a characteristic white coating was observed on the turbine stator blades and turbine blades due to the impact of using emulsion fuel on the operating parameters and emission from the miniature GTM120 gas turbine, described in [21] and [20]. It looked like chalk dust. During these experimental studies, a fuel-water emulsion with a water content of 3% to 12% with 2% emulsifier (by weight) was used. After these tests, no green glassy deposits were observed, and contamination in the form of a white "chalky" deposit was dominant. Unfortunately, photographic documentation of this phenomenon has not been preserved.

4. Conclusions

Based on the authors' observations and literature data presented in the article, the following conclusions are as follows:

- A greenish glassy coating on the hot section of the engine caused by the combustion of emulsion fuels containing a surfactant is caused by the presence of an emulsifier in the fuel mixture.
- The characteristic white coating on hot parts of the engine is not caused directly by the combustion of the emulsifier. The emulsifier can contribute to its formation, but these are at most synergistic effects that will not occur without water.
- During the combustion of the fuel-water emulsion with the addition of an emulsifier, the possibility of deposit formation on the elements of the hot part of the gas turbine should be taken into account and controlled.

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