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A METHOD OF ASSESSING THE TENDENCY OF AVIATION FUELS TO GENERATE THERMAL DEGRADATION PRODUCTS UNDER THE INFLUENCE OF HIGH TEMPERATURES

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Abstract

The subject of the article concerns the issues associated with thermal degradation of aviation fuels under high temperature conditions. Due to the intensive development towards increasingly higher thermal loads for both, turbine aviation engines, as well as the used fuels, the issue of thermal stability of the fuel itself is extremely important. In aviation, the fuel, apart from direct participation in energy generation during the combustion process of a fuel-air mixture, also takes part in the heat transfer in many aircraft systems. As a result, requirements in terms of the fuel's thermal potential are increasingly higher. The standard method for determining the thermal stability of fuel executed on a JFTOT device proves to be insufficient in the context of the appearing issues in current operation. The article presents a non-standard approach to the assessment of aviation fuel thermal degradation with the use of a specialist test rig. The authors believe that the presented methodology and the measurement capabilities of the test rig are valuable supplementary material for the standardized thermal stability test. It allows more thoroughly understanding the phenomena undergoing in the fuel impacted by high temperatures. The article has been prepared within the research project no. 2011/01/D/ST8/06567 funded by the National Science Centre in Poland.

Keywords: *jet fuel, turbine engine, thermal stability, test rig, non-standard method*

1. Introduction

Since the primary function of aviation turbine fuel is to power an aircraft, energy content and combustion quality are the key fuel performance properties. Combustion quality is dealing with jet fuels' thermal stability [4, 5, 6, 7]. The reason, why thermal stability is so important, is that it is actually used in planned the production of future gas turbine engines, which use jet fuel as their primary heat sink.

Commercial jet aircraft use fuel as a heat sink for cooling avionic and hydraulic systems. After absorbing heat, only a fraction of the fuel is burnt, and the rest is recycled back into the fuel tanks, to undergo the heat exchange processes [8]. As jet fuel during aircraft operation is subjected to high thermal loads (very low temperatures in wing fuel tanks and fuel lines, high temperatures in heat [20, 21]. Actually, more and more systems in aircraft require intensive cooling, so the need to increase jet fuel's "thermal capacity" is a critical factor. Considering the above, it can be clearly seen that the issues of fuel heat sink potential and the possibility of increasing thermal capacity of fuel, in particular, are important for the maintenance of aircraft propulsion systems [9, 10, 11].

Thermal degradation leads to the formation of solid deposits and gums in aircraft fuel system [12, 13, 14, 15], and specifically in fuel nozzles. Thermally generated deposits are detrimental to efficient operation of aircraft engines and may cause damage in the engine's hot section, especially the combustor region, i.e.:

- blocking fuel nozzles and fuel nozzle support, leading to thermal damage of combustor due to uneven flame pattern with some regions much hotter than the flame pattern produced by a nozzle in pristine condition;
- damage of turbine vanes and blades due to hard deposits flowing with flame and exhaust gases;
- changes in burner outlet temperature profile leading to significant shortening of turbine blades life.

The pictures below (Fig. 1-3) show some photographs of this problem.

Fig. 1. Carbon deposits on jet engine injectors (photographs taken during engine overhaul) [1]

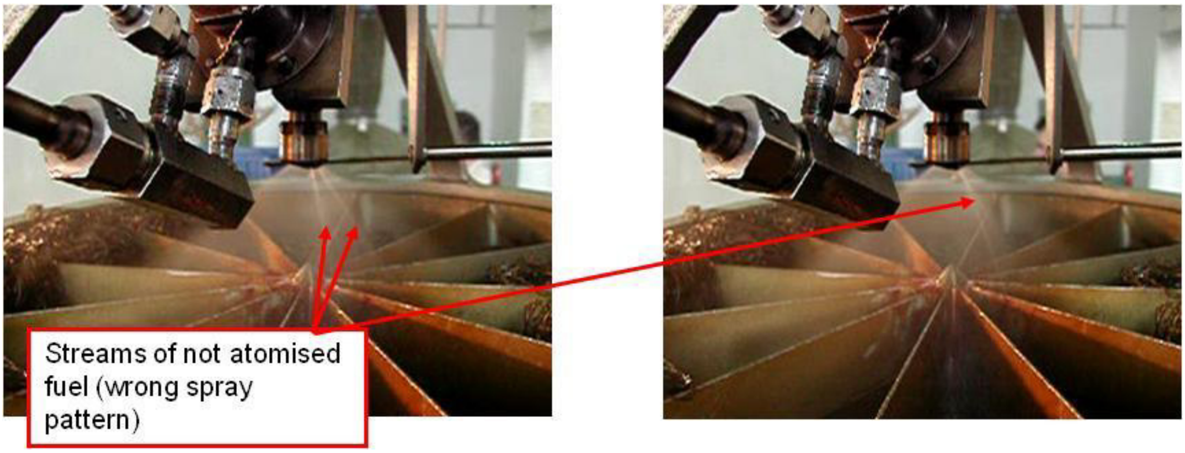

Fig. 2. Uneven flame pattern caused by carbon deposit on a fuel injector [1]

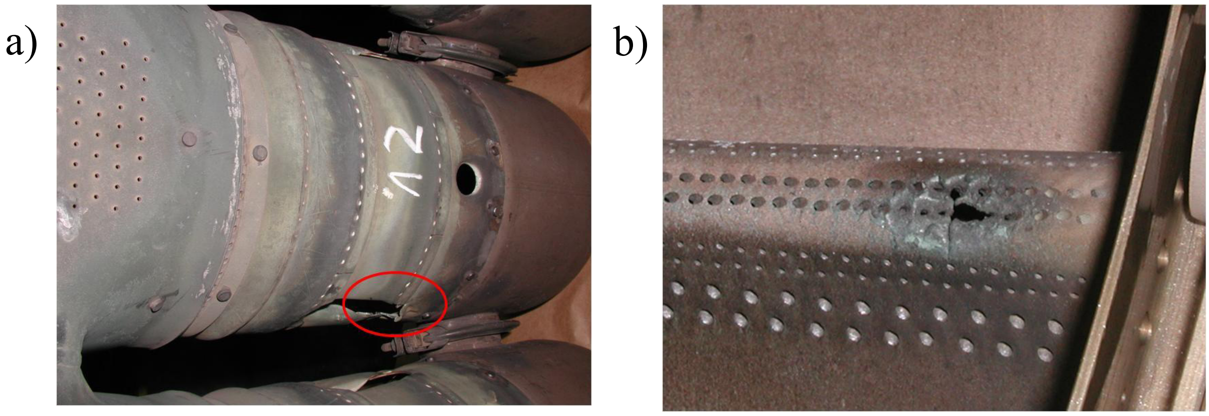

Fig. 3. (a) Combustor damage caused by uneven flame pattern, (b) turbine vane damage caused by hard carbon deposit, uneven flame pattern and disturbances in the temperature pattern in a combustor due to deposit formed on fuel nozzles [1]

The current specification requirement for measuring the thermal stability of jet fuel is the Jet Fuel Thermal Oxidation Tester (JFTOT) [2]. The method involves passing pre-conditioned fuel over a heated tube and then through a filter to trap any filterable insolubles formed during the test. The fuel is rated partly by the extent of filter plugging (indicated by a pressure drop across it) and by the visual appearance of the deposits on the heated tube [16, 17, 18, 19]. This method has some disadvantages that make the results not fully correlated with the problems occurring in jet engines during their operation. In other words – even though jet fuel passes the JFTOT test (results are positive), it does not mean that it has sufficient "thermal stability" to withstand the temperature changes in the course of the engine's normal operation. Additionally, JFTOT data have been reported to correlate poorly with the thermal deposit results from different engines' manufacturers (OEMs) test rigs, which were designed to simulate the aircraft engine fuel system and it was stated that they do not reflect real tendency of the jet fuel to form carbon deposits. The main reasons seem to be:

- the short test duration of the JFTOT (2.5 hr). This was the explanation given to account for the beneficial effect of MDA (the commonly used metal deactivator, N,N'-disalicyclidene-l,2-propane diamine), observed in the JFTOT;
- the differences in flow velocities, for example, in the JFTOT, the fuel flow are laminar (3 ml/min) whereas in aircraft operating systems, the flow is turbulent.

Based on the above, it seems justified to conduct non-standard tests, which would supplement standardised methodology (JFTOT) in order to better study and understand the influence of high temperature on fuel properties [23, 24].

2. Experimental details

Testing the course and dynamics of the aviation fuel thermal decomposition process in high temperature conditions is conducted with the use of a specialized test rig. The rig was constructed within the implementation of a research project financed by the National Science Centre. It is a unique research solution in the scope of the above field. It enables to conduct test-rig tests over a wide temperature (up to 600ºC) and pressure (ca. 17 MPa) ranges, which allows the simulation of operating conditions of various fuel systems.

The general view of the test rig with marked elements is shown in Fig. 4. Detailed data regarding the construction and measurement capabilities of the test rig are presented in [5, 6].

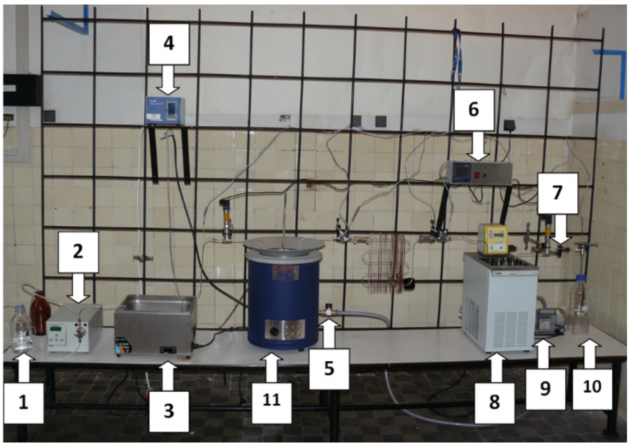

Fig. 4. General view of the test rig 1. vessel with the tested sample, 2. fuel pump, 3. water bath, 4. temperature controller in the sand bath, 5. sand bath air supply control valve, 6. recorder, 7. pressure valve, 8. cooling thermostat, 9. sand bath air dossing pump, 10. vessel for the tested sample, 11. sand bath

The basic idea of the conducted research involved the testing fuel flowing at a determined speed from the system constructed on the base of a stainless-steel tube. The pumping process is ensured via the operation of a piston pump, while the pressure in the system is set through a pressure valve. The fuel pumped in the system is subjected to high temperatures. Initial heating of the flowing fuel takes place in a water bath, while the operating medium is appropriately acted upon in a sand bath. The final section of the system is responsible for cooling the fuel down to a temperature value below the self-ignition temperature and for accumulating the tested fuel.

The study determining the thermal stability via standard research methodology [2] involves subjecting a specific amount of fuel to the impact of standardized operating conditions of a fuel system. The tested fuel is pumped at a constant volume rate – 3.0 ml/min, at a fixed pressure of 3.45 MPa, and the temperature is usually maintained at a level of 260 ºC, while the test time is 2.5 hours. The determination result is generally based on the qualitative method, which involves assessing the formed deposit according to a specified scale of patterns. Pursuant to the assumptions of this methodology, the tested fuel is subjected to the conditions corresponding the ones present in fuel systems of turbine engines. However, the structural development of aviation engines as well as the fuel themselves over the recent years, towards greater loads (thermal, in particular) caused the results obtained on the basis of this determination often not to be correlated with the conclusions stemming from current operation. The issues of modifying the research methodology in the scope of determining thermal stability has been already indicated in the paper [3].

This article presents a non-standard approach to the issues of assessing the tendency of aviation fuels to generate thermal degradation products under the influence of high temperatures. The research is conducted with the use of a dedicated laboratory test rig, presented in sub-section 2.1. The main advantage of the presented methodology is based on the wide measurement capabilities of the test rig, mainly in the scope of setting different test conditions:

- temperature in the system – up to 600°C,
- operating pressure – to ca. 17 MPa
- flow speed in the range of: 0.01-10 ml/min.
- test time depending on the amount of fuel and the flow speed of the operating medium.

Setting different flow values at the test rig, and thus, the thermal impact on the operating medium in the hot section, creates a possibility to simulate different conditions, which appear in the course of the actual operation of technical systems associated with fuel.

Under the assumption of the tested fuel sample staying at a constant level of 720 ml, depending on the adopted flow rate in the operating system, the sample test time was given in Tab. 1.

Tab. 1. The fuel test time depending on the flow rate in the measurement system

Flow	Test time
1.5 ml/min	480 min (8 h)
3.0 ml/min	240 min (4 h)
4.5 ml/min	160 min (2 h 40 min)
6.0 ml/min	120 min (2 h)

Examining a fuel sample at various set conditions, i.e., at different temperature, pressure and flow rate settings of the operating system, is the key better to understand the phenomena undergoing in aviation fuel subject to high temperatures. The more so that, on the basis of Fig. 5, we can see that aviation fuel is subject to different thermal degradation processes, depending on the assumed temperature.

An important element of this methodology is recording additional operating parameters of a fuel system. The following parameters are recorded with a measuring system during studies at a laboratory test rig:

1) temperature in the sand bath;
2) temperature downstream of the sand bath;
3) temperature upstream of the sand bath;
4) pressure upstream of the sand bath – in Fig. 6 „pressure in point 1";
5) pressure downstream of the cooling thermostat – in Fig. 6 „pressure in point 2";

An exemplary course of changes of the a/m parameters during the conducted tests is shown in Fig. 6 and 7. The results shown in Fig. 6 are extremely important, since their interpretation may be an initial signal regarding the occurrence of irregularities in the operation of a working system. If, during a conducted test, the fuel undergoes thermal degradation in the form of deposits appearing in the system (in the hot section of the test rig) under the influence of high temperature, the pressure values measured at measurement points 1 and 2 should be different.

Another advantage of the presented methodology, especially in the case of identifying deposits in the system, is the possibility to disassemble a part of the structure, a steel tube structure in the shape of the letter "U" (Fig. 8) located directly in the sand bath operating space. After completing a given test, such a part is disassembled from the system and is subjected to further analyses aimed at assessing the formed deposit.

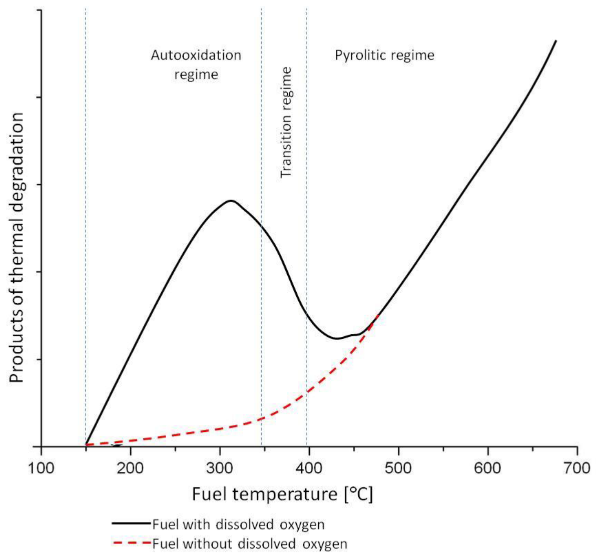

Fig. 5. Aviation fuel thermal degradation stages [22]

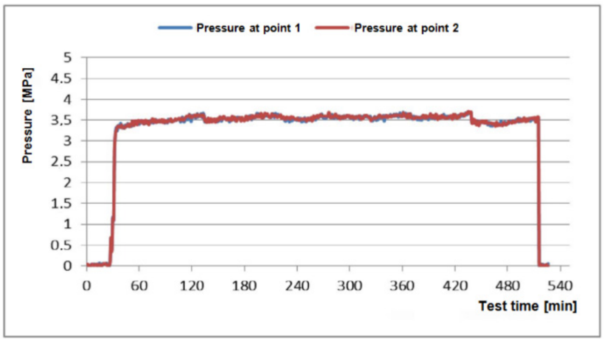

Fig. 6. The course of pressure changes in the system during a conducted test – set sand bath temperature: 300°C, flow 1.5 ml/min [19]

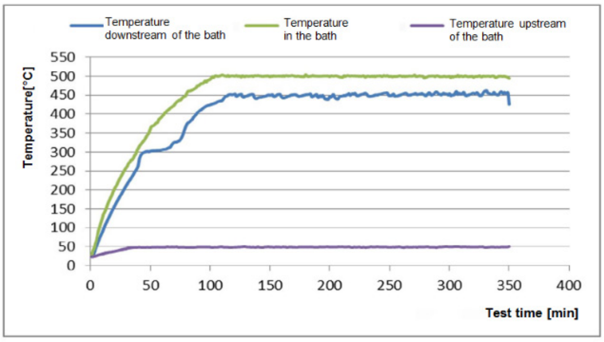

Fig. 7. The course of temperature changes in characteristic locations of the system during a conducted test – set sand bath temperature: 500 °C, flow 3.0 ml/min [19]

Another important aspect of the methodology is the assumption that after pumping a given amount of fuel through the test system in determined conditions, a fuel sample is each time appropriately marked and then sent to a laboratory in order to determine selected physical-chemical properties, i.e., hydroperoxide number.

3. Exemplary results

Fig. 9-14 presents the selected results obtained in the course of the test rig studies according to the non-standard method. Some results were further discussed in the paper [22].

4. Conclusions

The topics addressed in this article concerned the issues associated with the fuel thermal degradation process in high temperature conditions. It was emphasized that it is an important issue due to the constant development of the aviation engine design, as well as the fuels themselves, especially in terms of their operation in the conditions of the increasingly higher thermal loads.

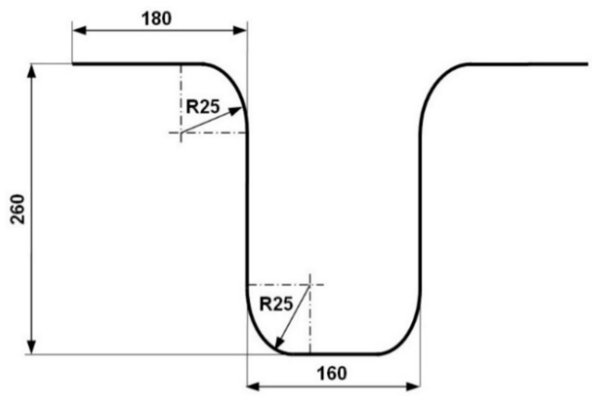

Fig. 8. Shape of a steel tube located in the sand bath operating space with the feature of to disassemble this part of the structure

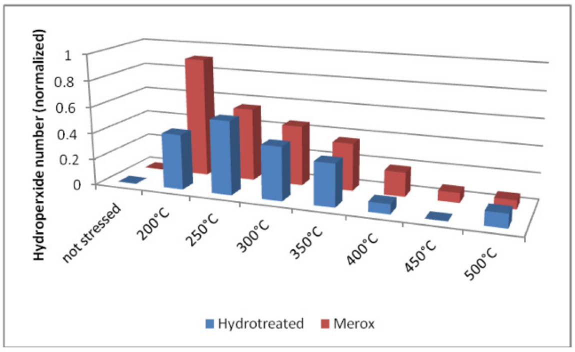

Fig. 9. Hydroperoxide number of thermally stressed jet fuels (flow speed 3 ml/min, pressure 3.5 MPa) [22]

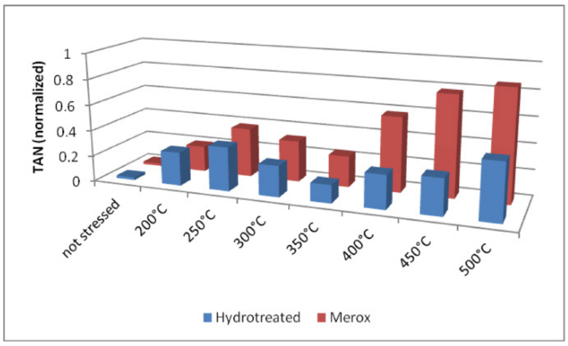

Fig. 10. Total Acid Number (TAN) values of thermally stressed jet fuels (flow speed 3 ml/min, pressure 3.5 MPa) [22]

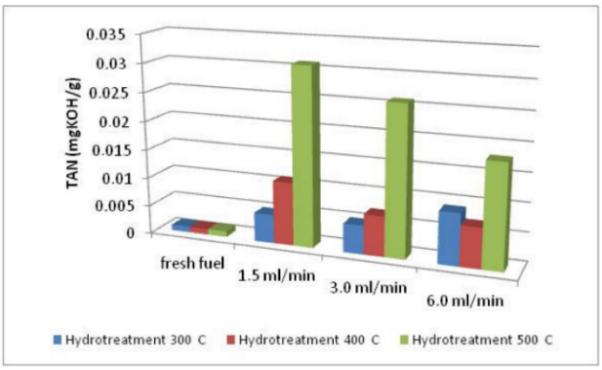

Fig. 11. Comparison of Total Acid Number (TAN) values of thermally stressed hydrotreated jet fuels (different flow speeds, different stressing temperatures, pressure 3.5 MPa)

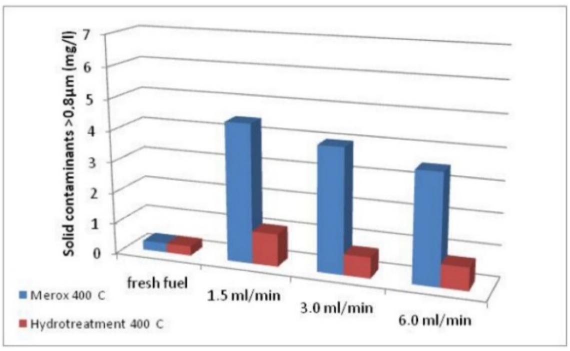

Fig. 12. Comparison of solid contaminants formed in thermally stressed jet fuels from different production processes (different flow speeds, constant stressing temperature 400°C, pressure 3.5 MPa)

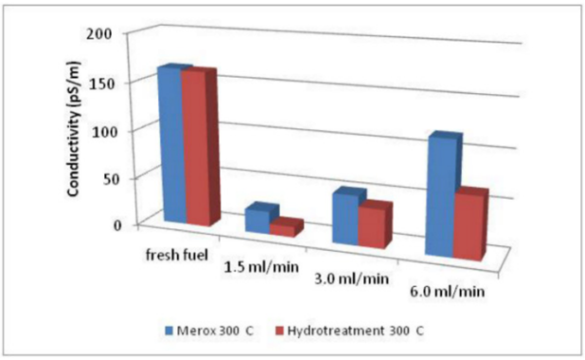

Fig. 13. Comparison of conductivity values of thermally stressed jet fuels from different production processes (different flow speeds, constant stressing temperature 300°C, pressure 3.5 MPa), presenting conductivity degradation (additive depletion) with increased stressing time (regulated by fuel presence time in the test rig hot section)

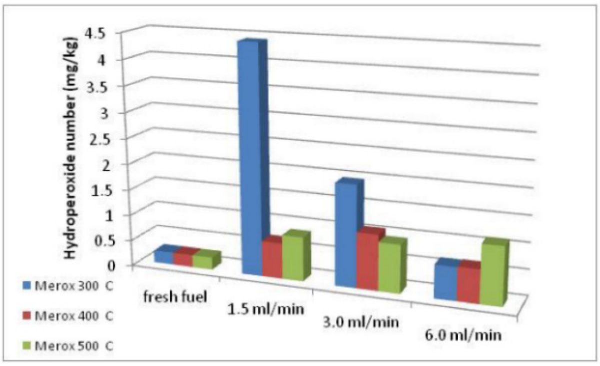

Fig. 14. Comparison of hydroperoxide number of thermally stressed Merox jet fuel (different flow speeds, different temperatures, pressure 3.5 MPa), presenting hydroperoxides formation being dependant on temperature and thermal stressing time (regulated by fuel presence time in the test rig hot section)

The standard fuel thermal stability determination methodology proves to be insufficient, in light of the occurring operational problems. Therefore, it was suggested to conduct supplementary tests using a specialist test rig and according to a non-standard method. It is most important assumptions and advantages in relation to the JFTOT tests were presented. Various, selected results of the previous test rig studies with the use of Jet A-1 fuel was also presented.

The non-standard test methodology together with a dedicated laboratory test rig seems to be a very interesting research solution, especially in the scope of thermal stability of alternative aviation fuels – biofuels. The results for pure petroleum jet fuel obtained in accordance with the standardized research method do not often correlate with the cases of actual damage proving thermal degradation of the fuel. Similar results can be expected in the case of using biofuels. Therefore, it is necessary to search for and test new research methods, which would more thoroughly reflect a given phenomenon.

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