



Degradation monitoring of aviation hydraulic fluids using non-dispersive infrared sensor systems



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ARTICLE INFO

Article history:

Received 2 June 2015

Received in revised form 2 October 2015

Accepted 15 October 2015

Available online 26 October 2015

Keywords:

Hydraulic fluid monitoring

Optical sensors

Non-dispersive infrared

Water content

Total acid number

Scavenger depletion

ABSTRACT

In commercial aircrafts, flaps, slats, tail plane fins and landing gears, i.e. all kinds of safety-critical mechanical subsystems are powered by hydraulic actuators. The mechanical power produced by these actuators stems from pressurized hydraulic fluids, which for reasons of passenger safety need to be fire-resistant. Phosphate-esters fluids, which are widely used for this purpose, are hygroscopic in nature and therefore susceptible to thermal degradation as flight operations are carried out. The paper demonstrates that the processes of water take up and thermally stimulated hydrolysis can be monitored with the help of non-dispersive infrared systems. In addition, such systems yield valuable information about the degree of acid scavenger depletion. With the information provided by such sensor systems innovative aircraft maintenance schemes can be implemented with a high cost cutting potential.

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1. Introduction

In the interest of passenger safety hydraulic systems in commercial airplanes need to be powered by fire-resistant phosphate-ester fluids [1–5]. A severe downside of such fluids is that these are hygroscopic in nature and therefore likely to take up water from the environment through air-pressurized reservoirs and through unavoidable small leaks in pipes, pumps and actuators. Absorbed water in connection with Joule heat, in turn, can damage phosphate ester fluids through hydrolysis. Reaction products which emerge from such reactions are various alcohols, which compromise the force-transmitting potential of the hydraulic fluids, and – more importantly – a range of phosphorous-containing acidic compounds, which can react with the remaining water contamination to produce corrosive hydronium ions [6]. As such corrosion damage is hard to localize and expensive to repair, an effective quality monitoring of aviation hydraulic fluids forms an important part of the current aircraft maintenance schemes. To date such maintenance is carried out in a discontinuous way, normally during comprehensive C-checks, with a frequency of once per year or even less [7]. The reason for this low frequency is that the water content and the acidity of the hydraulic fluids can only be assessed by taking samples from the pressurized hydraulic systems and by sending the

tapped samples to a number of specialized laboratories scattered across the world. The consequence of such procedures is that fluid maintenance is either performed too late or, much more likely, that proactive maintenance is performed, both with a negative financial impact on the airliners operating those planes.

More cost-effective maintenance schemes can be implemented when sensor systems become available which allow relevant fluid parameters, such as the water content and the acidity level, to be monitored with a much higher frequency, ideally after each flight or during overnight ground stops. In such an event fluid degradation trends can be established and deadlines for necessary maintenance operations can be estimated. First steps into this direction have shown that non-dispersive infrared (NDIR) sensor systems can potentially provide such information [8–10]. Following these initial feasibility tests, a German public funded research project named NAMIFLU (Nanotechnologie basiertes Mikrosystem zum in situ-Fluidmonitoring) was set up, in which the entire sensor system hardware had been completely redesigned and re-developed to comply with the harsh environment conditions encountered in practical aircraft operation. In this redesign process, in particular, all MEMS components such as the thermal infrared (IR) emitters and the thermopile sensor arrays had undergone rigorous testing and significant hardware improvements. Additionally, and as a central element, a silicon-LTCC-silicon microcuvette has been realized that guides the fluid under test through the optical gap in between the MEMS IR emitter and the thermopile sensor array, thus forming a complete micro sensor system. All these hardware-related

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improvements have been described in a conference paper by other NAMIFLU partners and the interested reader is referred to this publication for further details [11].

In the present paper our main focus is on those innovations that have been enabled through a better understanding of the fluid degradation process, through improved thermal fluid degradation protocols and a more detailed assessment of those optical features that signify fluid contamination and fluid degradation conditions. With this improved understanding at hand, optical features signifying the water content (CW), the total acid number (TAN), and the remaining acid scavenger reserve (ASR) could be identified within the complete set of currently used aviation hydraulic fluids. With the new feature of ASR monitoring in particular it has become possible to estimate the remaining fluid lifetime and to determine deadlines for urgently needed maintenance operations without tapping any fluid from a pressurized hydraulic reservoir – a task which has previously been impossible to perform. With this possibility at hand AIRBUS is now in a position to introduce an innovative aircraft maintenance scheme, which will allow necessary maintenance activities to be strategically planned and to be carried out at times and in locations of choice with minimal interruptions in the normal flight schedules, i.e. an innovation that will significantly reduce aircraft operation costs.

2. Aviation hydraulic fluids and fluid degradation

Depending on the aircraft's use profile different kinds of phosphate-ester fluids or blends thereof may be used. For the sake of definiteness we consider in Fig. 1 the degradation of a di-butyl-phenyl-phosphate-ester fluid. This figure shows how, through successive hydrolysis steps, a single molecule of base fluid (Fig. 1a) is degraded into one molecule of phosphoric acid, two molecules of butanol and one phenol at the end (Fig. 1d). Also illustrated in Fig. 1 is that, in addition to the H_3PO_4 itself, two more acidic partial phosphates are produced as degradation proceeds (Fig. 1b and c). Considering the fact that many different kinds of phosphate-esters with a range of different side groups are in use, it is obvious that a large number of different acids are potentially produced as aviation hydraulic fluids are being degraded.

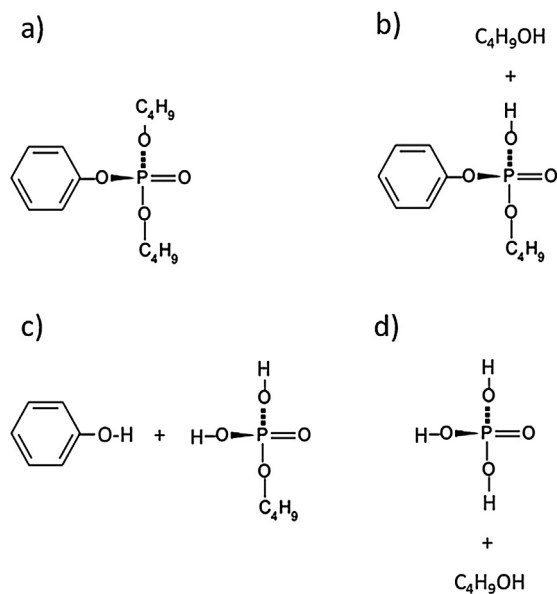


Fig. 1. Stepwise disintegration of a di-butyl-phenyl-phosphate ester fluid by means of hydrolysis: (a) base fluid, (b) after separation of a butyl group, (c) after separation of the phenyl group, and (d) after separation of the second butyl group and the formation of phosphoric acid.

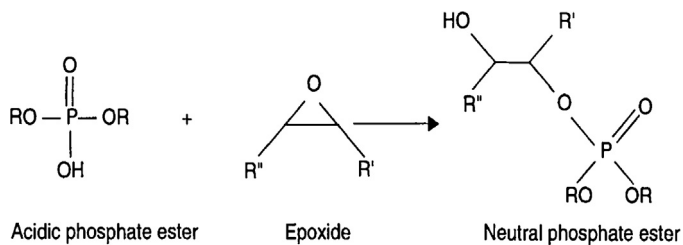


Fig. 2. Transformation of an acidic partial phosphate into a neutral phosphate via interaction with an epoxide scavenger molecule [12].

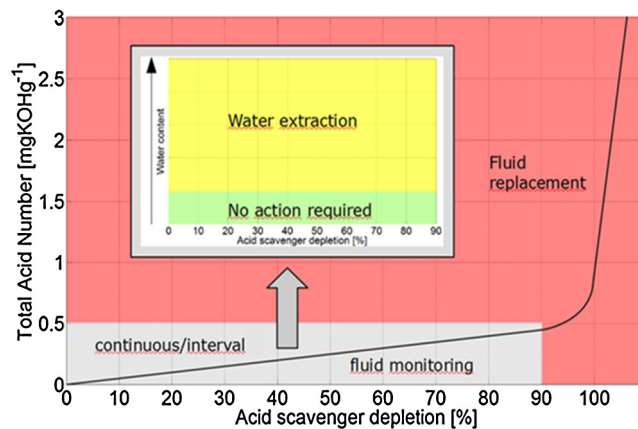


Fig. 3. Variation of the TAN value with usage time of an aviation hydraulic fluid. A rapid rise towards unacceptably large TAN values occurs after all scavenger molecules have been used up. The inset indicates low-effort maintenance options which can be taken during the initial phases of fluid degradation.

Once moisture has penetrated the fluid, the above-described degradation processes set in. In every hydrolysis event, a hydrocarbon side group is broken off from a phosphate-ester molecule and an acidic partial phosphate is generated. With each of these partial phosphates appearing, the danger is increased that corrosive hydronium ions will turn up. This danger, however, can be counteracted by adding epoxide scavengers to the base fluid [12]. With these acid scavengers being present, acidic partial phosphates tend to be transformed into neutral phosphates as shown in Fig. 2.

With most of the acidic partial phosphates being neutralized, a rapid rise in the TAN value is prevented and corrosion is inhibited. A severe downside of this kind of chemical protection, however, is that fluid degradation goes on for a long time without noticeable changes in TAN and that a rapid rise in the TAN value occurs, once the acid scavenger has become depleted. The rapidity of this rise is further augmented by the onset of autocatalytic reactions, which speed up the hydrolysis reactions once the co-generated acid phosphates are no longer neutralized. This latter unfavourable situation is illustrated in Fig. 3.

Considering the rapidity of the TAN increase after the acid scavenger reserve had become depleted, urgent action needs to be taken. It is therefore recommended that aircrafts should be grounded after TAN values have risen beyond $TAN \sim 1.5$ mg KOH/g. In case this happens at undue time in an airfield with poor infrastructure, long interruptions of the flight schedule and high costs may occur. In order to avoid such unfavourable situations, a most valuable piece of sensory information would be knowledge about the remaining acid scavenger reserve (ASR). We show below that such information becomes available by comparing the spectroscopically accessible concentrations of acid phosphates and split-off alcohols.

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