ON-BOARD MONITORING OF FUEL PROPERTIES

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Abstract

Several kinds of kerosene fuels, produced in different countries, can be used on helicopters powered by turbine engines (e.g. JET A / A-1, JP-5, JP-8, Russian TS-1, Chinese N°3 Jet fuel ...). Furthermore, kerosene fuels such as JET A and JET A-1 can be obtained from either crude oil or non-conventional sources (eg. lipid based fuels, sugar cane, coal, natural gas etc). As a result, the dispersion of certain fuel characteristics is not negligible, even if the fuels meet the fuel specification requirements.

Fuel systems of tomorrow will almost certainly have to adapt in order to be able to provide an increasing level of operational performance, regardless of the type of fuel used and how they were obtained (through from crude oil or alternative pathways). This should require developing new capabilities, to minimize the effects of the dispersions mentioned earlier on the three main fuel properties involved in the design and performance of the fuel system: density, viscosity and dielectric constant. In parallel, any other complementary information, such as presence of bio contamination could also be part of the useful information to flight crew and maintenance staff in the future.

1. AVIATION FUELS AND ADDITIVES: A COMPLEX WORLD IN CONSTANT EVOLUTION

1.1. Today‘s fuels

Helicopters are employed in a wide variety of missions (military, search and rescue, off-shore transportation) all around the world. All these missions are conducted using the fuels available in the country or organization operating the aircraft. The most common kerosene fuels in western countries are the JET A-1 (in Europe) and the JET A (in the USA). On the military aspect, NATO armies have their own standards and specific kerosene (JP-8, JP-5 with respective NATO codes F-34 and XF-43). In certain countries outside Western Europe or the USA, helicopters are operated using specific fuels such as TS-1 in Russia [4] or Jet Fuel n°3 in China [5].

Even if these fuels appear similar from a chemical point of view (they all belong to the kerosene fuels family), they are produced according to different specifications, which can result in non-negligible differences. The TS-1 specification requires a minimum density of 780 kg/m^3 [4] while the JET A-1 density shall be between 775 and 880 kg/m^3. With regards to the viscosity, both the Russian and ASTM norm require a max viscosity of 8 cSt at -20°c. The CRC handbook [8], however, states that the viscosity of TS-1 is significantly lower than that of Jet A-1’s. Lastly, it is worth nothing that none of the fuel specification explicitly specifies any value for dielectric constant.

Recently, the US army has launched the production of two new fuels, called F-24 and F-27, in replacement of the existing JP-8 and JP-8 +100.

These fuels can be mixed with additives - the list of which is being detailed in the specification, as well as the concentration limits for each of them.

Below is a list of the most common fuels generally found in the flight manuals of today’s helicopters:

JET A-1:	Civil, Western Europe
JET A:	Civil, USA
TS-1:	Civil, Russia, CIS [4]
JP-5:	Military, NATO, Naval [7]
JP-8:	Military, NATO [6]
JP-4:	Military, NATO [7]
Jet Fuel n°3:	Civil, China [5]

Figure 1 Refueling of the H175

1.2. Fuels obtained from non conventional sources

All the fuels listed above have been produced mainly from crude oil for decades. However, alternative methods have since been developed by the petroleum industry in a constant effort to find and establish sustainable sources. For example, the SASOL Company in South Africa has been producing JET A-1 from gas and coal for more than twenty years. More recently, two additional alternative methods were added to appendices of the JET A-1/A specification: HEFA and SPK.

The validation of obtaining JET A or Jet A-1 from non-conventional ways is done through an international process involving the ASTM committee and a large number of OEMs, oil companies, engine manufacturers and fuels system suppliers. The validation is based on the principle of the « fit-for-purpose » properties. This means emphasis is placed not on how the fuel is produced but rather if the final product complies with:

- The specification of JET A/A-1 through compliance to ASTM D 7566 [2], created specifically for non-petroleum fuels in 2009
- The material compatibility specification (ASTM-D-4054) [3].

As mentioned previously, the ASTM-D-1655 [1] already includes three appendices. Nevertheless the number of candidates proposing new manufacturing processes is on the rise, and the specification will most likely be revised frequently in the years to come to include new appendices (for instance, for fuel obtained from biomass, alcohol, algae, sugar, industrial waste etc.). This trend extends well beyond the borders of western countries: for example similar processes to obtain fuels via alternative methods are also being put in place in China under their own standards.

1.3. A lasting trend

The world of fuels is in constant evolution, and the development and use of new alternative kerosene is inevitable. This is probably a lasting trend.

It is the responsibility of all the stakeholders (OEM's, petroleum industry, engines manufacturers, fuel systems suppliers…) to be represented in the international committees to closely follow the evolution of fuel production and to weigh in the validation process. However, tomorrow's fuel systems will have to adapt, through development of enhanced capabilities, in order to provide an increasing level of performance independent of the fuel production origin and process.

2. MAIN FUEL PROPERTIES DRIVING THE DESIGN AND PERFORMANCE OF A FUEL SYSTEM

The three main fuel properties driving the design and performance of a fuel system are: density, viscosity, and dielectric constant.

The majority of design studies of a fuel system are undertaken while considering the most conservative conditions to ensure that all possible situations are covered. For instance, calculation of the pressure loss through an engine supply line often requires considering the "worst" fuel (densest and most viscous). In these cases, the dispersion is ultimately covered by the conservative hypotheses and consequently has no visible impact on the crew during operations.

However, when it comes to the gauging system, the choice of the gauging system architecture can have a direct impact on the operation of the helicopter. For instance, a simple gauging system (without compensation) will be optimized by considering the average key characteristics of the most common fuel expected to be used in service. The accuracy of such a system is hence evidently affected when operating the helicopter with a fuel having different characteristics.

3. DISPERSION OF FUEL PROPERTIES

The CRC Aviation Fuels Handbook provides the fuel properties of the most common fuels, at different temperatures. Although this document serves as a reference for most fuel system designers, the properties given therein are average values while complementary studies have been performed to quantify dispersion of fuel properties. Incidentally, a worldwide fuel survey was conducted in 2006, and the findings were published in CRC document No. 647 (Fig. 3).

We now focus on dispersion of two properties of particular interest to fuel system design: density and viscosity:

3.1. Density

Figure 2 is an extract of the JET A-1/A specification, showing the range of acceptable density and viscosity (775-880 kg/m^3). Figure 3 gives a plot of the density measurements obtained during the survey. It shows that even when the density is within the specification limits, a non-negligible dispersion exists (approximately +/- 20 kg/m^3, i.e +/- 2.5 %).

Density at 15°C, kg/m³		775 to 840
FLUIDITY		
Freezing point, °C	Max	−40 Jet A[H] −47 Jet A-1[H]
Viscosity −20°C, mm²/s[I]	Max	8.0

Figure 2 Extract of ASTM-D-1655 (JET A and JET A-1) showing requirements for density

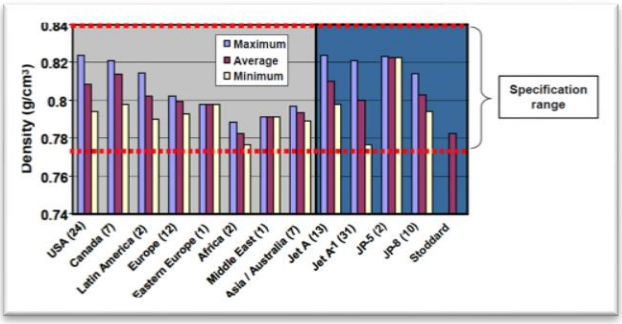

Figure 3 : Fuels density dispersion shown by CRC fuel survey

3.2. Viscosity

With regards to the viscosity, the JET A/A-1 specification requests a maximum viscosity of 8 cSt at -20°C (figure 2). The CRC survey shows that the there is a wide dispersion on fuel viscosity even though the fuels are well below this maximum limit (figure 4). The study also shows that a non-negligible number of fuels, whilst being compliant to the specification of 8 cSt at -20°C, exceed 12 cSt at -40°C, which is the maximum acceptable limit for engine manufacturers (figure 5).

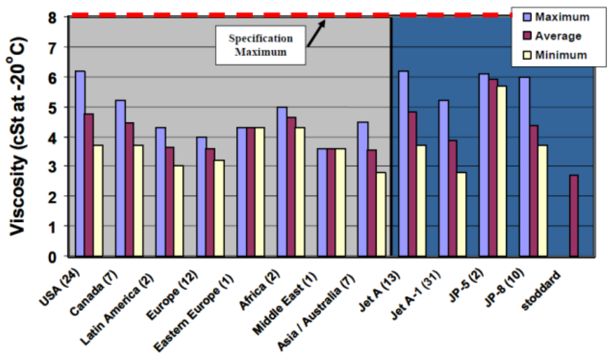

Figure 4 Fuels viscosity dispersion shown by CRC fuel survey

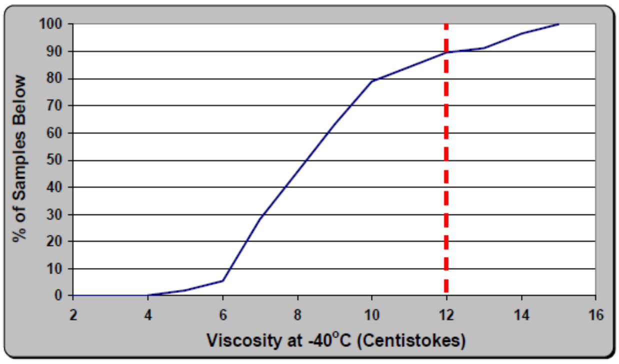

Figure 5 Actual viscosity at -40°C

4. POTENTIAL IMPROVEMENTS BROUGHT BY FUEL PROPERTIES MONITORING: "WISH LIST" AND TECHNICAL CHALLENGES

Monitoring fuel properties will not only further hone the accuracy of the systems, but will also provide additional support to crews and maintenance teams in their daily missions.

The following paragraph presents a "wish-list" of the potential benefits to gain from enhanced monitoring of these properties.

4.1. A density sensor to improve gauging system accuracy

The accuracy of a gauging system depends on a large number of parameters. The document AIR 1184 [10] provides an exhaustive list of all potential contributors of gauging errors, including bias and random errors. For instance, we find: gauging laws extrapolations, compensation type (temperature, dielectric, and density), number of probes per tanks, tanks shapes and modelling, non-gaugeable volumes, aircraft attitude, etc. Today's gauging systems sometimes feature look-up tables (tables linking H/C attitude, volume and height of fuel in the tank) which further enhances the precision of the gauging system vis-à-vis the geometrical profile of the tanks. The continually improving accuracy of CAD representations of tank models due to increasing capability of computers allows high level of details to be stored.

Lastly, it is worthwhile to note that AIR1184 emphasizes that: "the single most significant factor affecting capacitance-type gauging system accuracy, over which neither the airframe nor the gauging manufacturer has control, is the fuel itself".

Some of today's measurement systems already incorporate sensors like compensators (permittivity compensation), which enhance accuracy in measurements. In such systems, information given by the fuel probes is corrected using the reference permittivity returned by compensator. The permittivity value is used to derive the fuel density using the Clausius-Mossati relationship:

(1) $$D = \frac{k-1}{A+B(k-1)}$$

The figure below shows the dispersion obtained from another survey conducted by the CRC, including alternative JET A-1. The graph shows a dispersion of +/- 15 kg/m^3 approximately, i.e. +/- 1.9%).

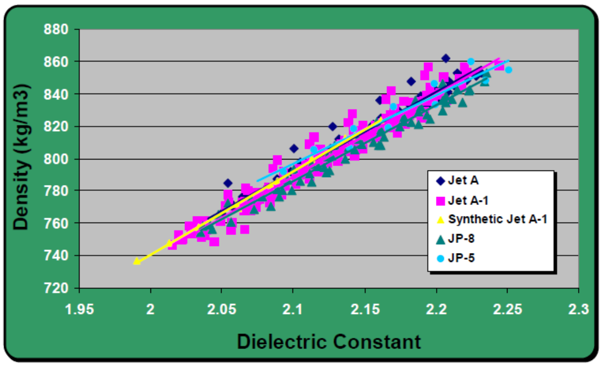

Figure 6

A note for reminder, helicopters fuel system gauging system is designed to meet the following accuracy:

- 2% of total capacity at low fuel quantities
- Increasing linearly to 6% of total capacity at tanks full

Therefore, it is understood that the direct reading of the density through a dedicated on-board sensor (that would eliminate the inaccuracy linked to the dispersion of the D vs K plot) would improve global accuracy. The ideal gauging system should feature both compensation probe(s) and density sensor(s).

Permittivity measurement (made possible by compensator probes) is used relatively often on today's helicopter systems. However, density sensors are used only on a few large airliners. Densitometers for helicopter applications therefore remain to be developed, which should take into account the following designs drivers applicable to rotorcrafts: size, weight, electromagnetic compatibility and vibrations.

4.2. A viscosity sensor to improve H/C availability

A common requirement in the engine installation manuals is to limit fuel viscosity to 12 cSt, in order to ensure proper atomization of fuel from the engine fuel nozzles. This is particularly important when considering cold starting and restarting of engines.

Nonetheless, as information on the fuel viscosity is generally not available to the crew, this requirement is translated into an equivalent fuel temperature requirement in the flight manual. This in turn may lead to unnecessary constraints on the fuel temperature envelope.

For instance, the CRC gives a viscosity of 12 cSt for JET A-1 at -40°C. Based on this value, the flight manual would then specify a minimum temperature of -40°C for this fuel in order to guarantee a proper functioning of the engine. As discussed earlier, non-negligible dispersion of viscosity exists across different fuels, and the viscosity of certain JET A-1 could be higher than 12 cSt. In order to take into account this potential dispersion, the engine manufacturer generally limits the cold fuel operation by considering the fuel with the most limitations to ensure that the viscosity will always remain below 12 cSt regardless of the fuel used. This in turn causes the minimum allowed temperature for JET A-1 to be at -29°C instead of -40°C.

This creates an operational limitation that could be easily removed if viscosity measurement is available on-board. In fact, the limitation in the flight manual would be provided directly in terms of viscosity (engine start allowed if viscosity is below 12 cSt).

4.3. Microbiological contamination detection to ease maintenance tasks

Biological contamination is a result of the growth of fungi and bacteria in fuel tanks at the interface between fuel and water. Most of the customers operating helicopters in tropical regions encounter such contamination. Indeed, warm and wet climate is an accelerating factor for the growth of microorganisms (figure 7).

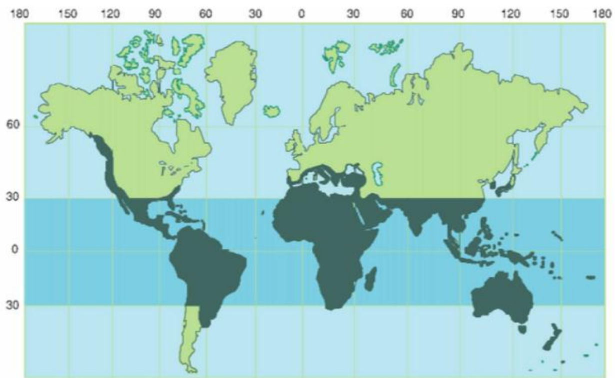

Figure 7 Higher risks climate zones for bio contamination

Figure 8 Damage of a fuel equipment plate due to Bio-contamination

The microbiological contamination can cause severe damage to the fuel tanks (see example on figure 8). Maintenance manuals provide recommendations for detection, preventive and corrective treatments. If contamination is detected, the use of a fuel additive called biocide is required at a concentration adjusted to the level of contamination.

The preventive treatment, used in the case of long term storage, prevents the growth of bacteria and fungus while the curative treatment, at higher concentration, is required in the situations where strong contamination has been detected on an aircraft.

There exist different methods to detect contamination: taking of samples and analysis performed by a laboratory, or an in situ analysis by the operator himself, using a detection test kit - the latter being faster but less accurate.

The periodicity of fuel sampling and analysis on A/C fuel is adapted to each particular case.

- For helicopters with low risk, at least once every six months is recommended.
- For helicopters with moderate risk, at least once every three months is recommended.
- For helicopters with high-risk, at least once a month is recommended.

In case of high level of contamination, maintenance personnel are required to initiate a treatment cycle where several detection tests would be necessary in a relatively short period of time (3 or 4 tests in a month).

Therefore, having an on-board contamination detection system would considerably simplify monitoring of fuel contamination and eliminate the need for regular sampling and abrupt corrective treatment

4.4. Other potentially interesting sensors

4.4.1. A turbidity sensor

Turbidity sensors measure suspended particles in a fluid. Installation of such sensor in a fuel system would allow the monitoring of fuel pollution/contamination and provide the following advantages:

- Early detection of problems of fuel purity, and identification of probable sources of pollution after fuel sample analysis (pollution coming from the fuel itself, from the piping, bladder tanks or fuel sstem components)
- Prevention of fuel clogging problems

Figure 9 Illustration of different levels of solid pollution

4.4.2. A FSII concentration sensor

A sensor measuring anti-ice additive concentration would help maintenance personnel to accurately control and adjust the concentration. This would prevent potential overdosing that have already shown to be problematic at high concentrations in terms of compatibility with some of the materials used in the fuel system components.

4.4.3. A Free and dissolved water sensor

Water detectors already exist and are fitted on certain helicopters. They provide binary output signal, indicating the presence or absence of water at the bottom of the tanks.

However, if for any reason, water is present at a relativity high and uniform concentration inside a fuel capacitive probe, the dielectric constant can be affected and lead to misleading indication of the gauging system [10].

5. TECHNICAL CHALLENGES

5.1. Fuel homogeneity

Monitoring of the fuel density in a helicopter fuel system would of course increase the accuracy of the system. Nevertheless, in order to cope with potential non-homogeneity of the fuel temperature in the tanks and feed lines, and with potential stratification phenomenon, the density measurement should be associated to temperature measurement so that the correction can be applied if necessary. For example, knowing the density and temperature of a given point in the fuel tank and fuel temperature at the engine inlet enables the calculation of density of the fuel at engine inlet, and therefore provide access to the accurate value of the fuel consumption.

As for the density measurement, the viscosity measurement should ideally associated to temperature measurements in order to be able to extrapolate viscosity values at other locations in the systems where fuel temperature may be different (for example at engine inlet).

The question of homogeneity will also have to be taken into account when considering a turbidity sensor or a FSII concentration sensor.

Lastly, the contamination detection sensor should be installed at the bottom of the tank, where free water, and consequently contamination, is expected to be present.

5.2. Helicopter environment

All sensors will have to be qualified for helicopter operating environment, which is often more severe than those of an airliner's, especially in the field of EMC and vibrations.

Also, size and weight must be compatible with helicopters applications, where available space is reduced compared to large A/C.

5.3. Safety

It is recalled that all electronic components installed inside a fuel tank must be shown to comply high level of safety requirements.

6. CONCLUSION

The world of fuel and additives, being in constant evolution, proves to be a challenge for today's fuel systems. On the other hand, it can be viewed as an opportunity to develop new functions for tomorrow's fuel systems. On-board monitoring of fuel properties would bring enhanced support to our operators - by increasing gauging accuracy, monitoring fuel viscosity for cold weather engine start or providing useful information to the maintenance personnel. Some of the sensors discussed in this paper already exist but are neither well adapted nor qualified for helicopter applications, while the others remain to be developed. There lay ahead of us, hence, a path of innovation. The development of such new products and functions will not only require one to address the technical aspects but also issues related to reliability and safety. Ultimately, the responsibility of fuel quality should lie with the oil industry.

7. REFERENCES

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[3] ASTM-D-4054 "Standard Practice for Qualification and Approval of New Aviation Turbine Fuels and Fuel Additives", ASTM

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[5] GB 6537-94 Chinese Jet Fuel Specification

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[7] MIL-DTL-5624 Detail specification, Turbine Fuel, Aviation, grade JP-4 and JP-5

[8] CRC report n°635, "Aviation Fuel Handbook", CRC

[9] CRC report n°647, "World Fuel Sampling Program"

[10] AIR 1184 Rev A "Capacitive fuel gauging systems accuracies", SAE