MISFUELING DETECTION WITH TWO OFFSETED CAPACITIVE FUEL SENDERS

*Dubravko, **MILJKOVIĆ**, HEP - Croatian Electricity Company, Zagreb, CROATIA,*

Contacts – mob: +385 98 9825602, e-mail: dmiljkovic@hep.hr

ABSTRACT - Misfueling of a general aviation aircraft with a Jet Fuel instead of an Avgas can have dire consequences. In this paper simple non-destructive testing method is proposed using two capacitive fuel senders that are vertically displaced in a fuel tank by a small distance to detect such situation. Method is based on different readings for the same fuel level in a tank (as fuel senders are displaced). Each fuel has different dielectric constant. In case of correct fuelling difference between these readings will always fall within narrow fixed interval.

1. INTRODUCTION

Misfueling is the introduction of an improper fuel into an aircraft's tanks. The consequences of misfueling can range from the benign (fuel system drainage) to the expensive (engine replacement) to the disastrous (engine failure shortly after takeoff), [1]. Misfueling is always potentially very serious event. The greatest danger for most general aviation pilots occurs when a gasoline (Avgas) engine is serviced with jet fuel (often know to general population as kerosene, but with commercial names Jet fuel A, A1, B, Avtur etc.). Most commercial turbine engines can be run on avgas within the limits listed in the Pilot Operating Handbook. However the gasoline engines cannot be run on jet fuel. If not supplied with fuel of a certain octane rating, a gasoline engine will stop working, be damaged or destroyed by detonation. Many practical aspects of misfueling prevention by conventional procedures for aviators are described in great detail in [1]. In this paper simple method is proposed using two capacitive fuel senders that are vertically displaced in a fuel tank by a small distance (i.e submerged to different depth in fuel) to detect such situation. Method is based on different readings for the same fuel level in a tank. Each fuel has different dielectric constant. In case of correct fuelling difference between these readings will always fall within narrow fixed interval. However in case of a misfueling, due to different dielectric constant of a mixture or layering of different fuels (before they mix) with different dielectric constants and capacitive fuel senders vertically submerged to different depths in different fuels, difference between readings will fall outside of the acceptable interval. In the later case warning will be issued and additional probe of fuel should be preformed. A lightly contaminated fuel (FAA test find it up to 6% volume mixture of Jet Fuel in Avgas acceptable for lean rating but still unacceptable for rich rating) would pass through with little or no detriment to engine. Requirement for accuracy of capacitive senders is proposed based on tolerable mixture.

1.1 DIELECTRIC CONSTANTS OF AVIATION FUELS

Dielectric constants of aviation fuels are presented in ***Table 1*** and ***Figure 1***, [2].

Table 1 *Dielectric constants of aviation fuels*

Fuel	*Temperature (°C)*		
	20	*40*	*60*
Avgas	*1,96*	*-*	*-*
Jet A, A1	*2,13*	*2,10*	*2,07*
Jet B	*2,06*	*2,03*	*2,00*

Jet fuel A and A1 have about 10% higher dielectric constant than Avgas.

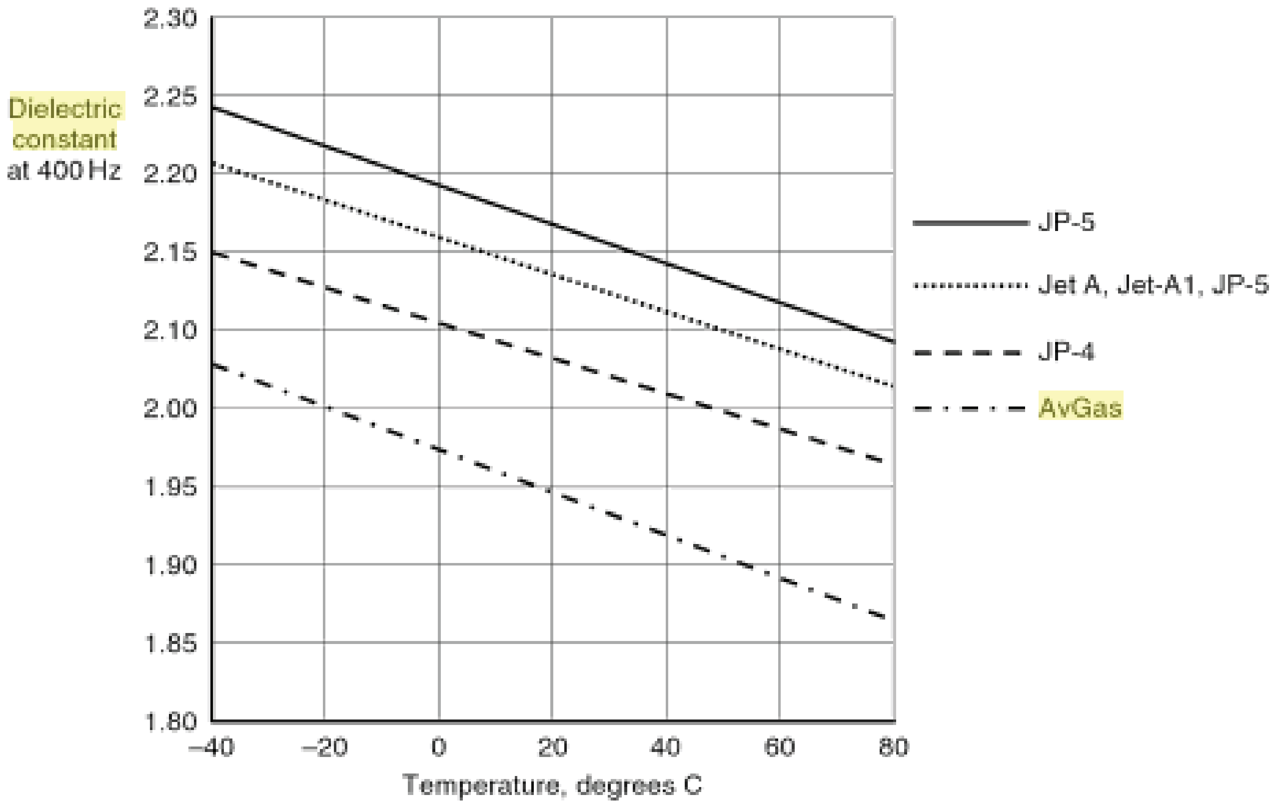

Figure 1 *Dielectric constant vs. temperature for typical aircraft fuel at 400 Hz (adopted from [2])*

1.2 DIELECTRIC CONSTANT OF THE FUEL MIXTURE

Dielectric constant of the fuel mixture can be determined by following equation:

$$k = pk_1 + (1 - p)k_2 \tag{1}$$

where

k is the dielectric constant of mixture
k_1 is the dielectric constant of fuel 1
k_2 is the dielectric constant of fuel 2
p is the volume part of fuel 1 in mixture, $0 < p < 1$

1.3 PRINCIPLE OF CAPACITIVE FUEL SENDER

Capacitive fuel sender is based on tubular capacitor probe where fuel becomes dielectric, as shown in ***Figure 2***, from [3]. Principal of operation is based on the difference in the dielectric properties of air and fuel, and described in great detail in [2]. At different fuel levels, different values of capacitance are measured and therefore the level of fuel can be determined. AC current is used in a process. As dielectric constants vary a little with temperature, better capacitive fuel includes thermal compensation. Device itself is without any movable or flexible parts. Advantages of capacitive fuel senders are high precision, high reliability and good cost performance.

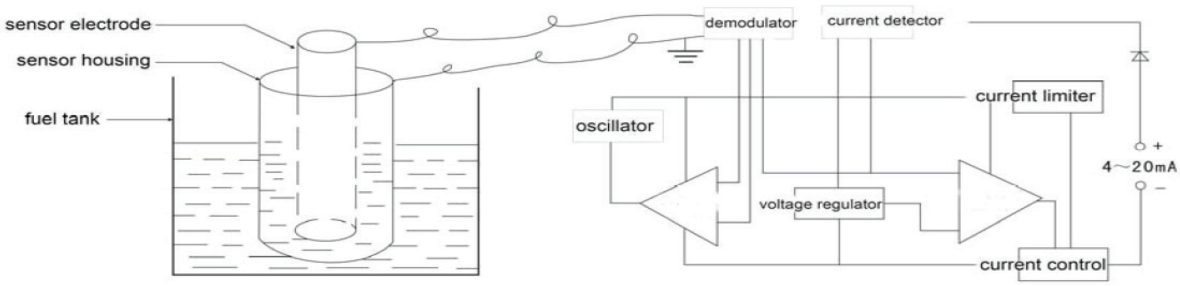

Figure 2 *Fuel level sensor schematic*

Theoretical capacitance of cylinder probe in vacuum is

$$C = \frac{q}{V} = \frac{2\pi\varepsilon_o L}{\ln(b/a)} \tag{2}$$

where is

L – length of probe
a – Outer radius of probe inner tube
b – Inner radius of probe outer tube

In a real life capacitance of a probe C_p consists of two parts: the effective capacitance C_{Peff} developed across the dielectric gap between the electrodes and the stray capacitance C_{Pstr} developed between the tube and other items like adjacent structure. The overall dry capacitance is expressed as

$$C_{Pdry} = C_{Peff} + C_{Pstr} \tag{3}$$

When the probe is fully submerged in a fuel of dielectric of *k* its capacity is

$$C_{Pfull} = kC_{Peff} + C_{Pstr} \tag{4}$$

$$C_{Pfull} = (k-1)C_{Peff} + C_{Pdry} \tag{5}$$

When the probe is partially submerged in a fuel of dielectric of *k*, where *n* is normalized value between 0 and 1, its capacity is expressed by

$$C_{nPfull} = n(k-1)C_{Peff} + C_{Pdry} \tag{6}$$

The change in capacitance $C_{pn\Delta}$ from air to partial submersion is

$$C_{Pn\Delta} = C_{nPfull} - C_{Pdry} \tag{7}$$

$$C_{Pn\Delta} = n(k-1)C_{Peff} \tag{8}$$

Electronic circuits supplied with the capacitive probe provide that a change in probe capacity is transformed to the output voltage proportional to the fuel level in a tank (e.g. 0 – 5 V range), where is *r* proportionality constant:

$$U_{out} = rC_{Pn\Delta} + U_{base} \tag{9}$$

After correct calibration U_{base} is set to 0 and output voltage is expressed by

$$U_{out} = rC_{Pn\Delta} \tag{10}$$

2. METHOD

Method uses two displaced capacitive fuel senders with temperature compensation. They are submerged into fuel to different depth, as shown in ***Figure 3***. First probe is submerged almost to the bottom of the fuel tank, while second probe is offseted (displaced) by 25% of the full tank fuel level (without some small amount of fuel under the first probe and bottom of the fuel tank). For the particular fuel level in a fuel tank readings from both senders will differ for a constant value (actually, readings will fall within narrow interval). If the fuel level in tank is greater than 25% of full capacity both probes will be submerged in fuel. Fuel senders have temperature compensation (due to slight change of dielectric constant of Avgas with temperature). Offset value of 25% was chosen arbitrary as a compromise between precision and necessary fuel level.

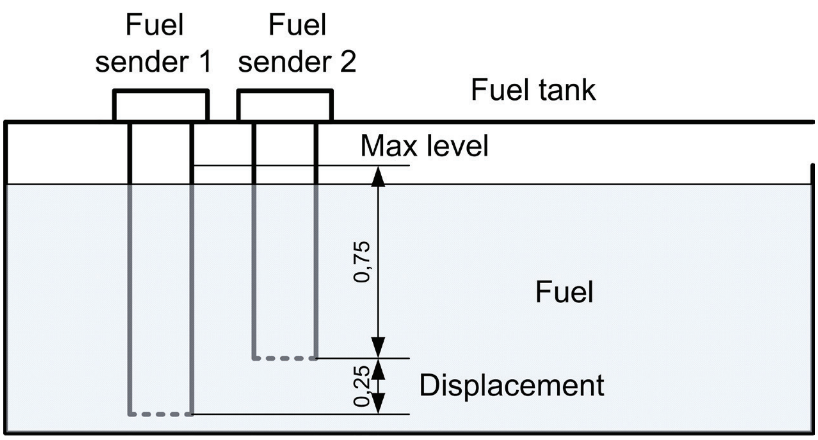

Figure 3 *Fuel tank with two capacitive fuel senders submerged to different depths (the diameter of fuel senders is enlarged in comparison with the tank for clarity purpose)*

If we assume that C_{Peff} is same in both fuel probes the capacity change from empty tank in the first probe is

$$C_{Pn\Delta,1} = n(k-1)C_{Peff} \tag{11}$$

The capacity change from empty tank in the second probe is

$$C_{Pn\Delta,2} = (n - 0.25)(k - 1)C_{Peff} \tag{12}$$

The capacity change between two probes is then

$$C_{P\Delta} = C_{Pn\Delta,1} - C_{Pn\Delta,2} \tag{13}$$

$$C_{P\Delta} = 0.25(k - 1)C_{Peff} \tag{14}$$

The output from fuel senders is voltage change proportional to change in capacitance:

$$U_{out,1} = rC_{Pn\Delta,1} \tag{15}$$

$$U_{out,2} = rC_{Pn\Delta,2} \tag{16}$$

$$\Delta U = U_{out,1} - U_{out,2} \tag{17}$$

$$\Delta U = r(C_{Pn\Delta,1} - C_{Pn\Delta,2}) \tag{18}$$

$$\Delta U = 0.25r(k - 1)C_{Peff} \tag{19}$$

where is

$U_{out,1}$ - the output voltage from the first fuel sender
$U_{out,2}$ - the output voltage from the second fuel sender

With the correct fueling difference *ΔU* will remain constant regardless of the fuel level within a tank (once the tank is full over 25% and both probes are submerged). However in case of misfueling, dielectric constant *k* of the mixture will change and so will difference *ΔU*. Differences in values of dielectric constants of different fuels are not very large, actually values are quite similar. For that reason it is necessary to detect subtle changes in *ΔU*.

$$\Delta U_{Avgas} = 0.25r(k_{Avgas} - 1)C_{Peff} \tag{20}$$

$$\Delta U_{Mix} = 0.25r(k_{Mix} - 1)C_{Peff} \tag{21}$$

where is

ΔU_{Avgas} - the difference between outputs of two fuel senders submerged in Avgas
ΔU_{Mix} - the difference between outputs of two fuel senders submerged in fuel mixture (Avgas and Jet Fuel).

3. RESULTS OF CALCULATIONS FOR FUEL MIXTURES

In real application the precision class of fuel senders should be considered. If *α* is the relative errors then the following relation is valid for Avgas

$$(1-\alpha)U_{out,1} - (1+\alpha)U_{out,2} < \Delta U_{Avgas} < (1+\alpha)U_{out,1} - (1-\alpha)U_{out,2} \tag{22}$$

and the following for the case of mixed fuels:

$$(1-\alpha)U_{out,1}-(1+\alpha)U_{out,2}<\Delta U_{Mix}<(1+\alpha)U_{out,1}-(1-\alpha)U_{out,2} \tag{23}$$

When considering the ratio ΔU_{Mix} / ΔU_{Avgas} in worst case scenario both relative errors in ΔU_{Avgas} will be the opposite direction of both relative errors in ΔU_{Mix}.

$$\frac{0{,}25r(k_{Mix}-1)C_{Peff}}{0{,}25r(k_{Avgas}-1)C_{Peff}}(1-4\alpha)<\frac{\Delta U_{Mix}}{\Delta U_{Avgas}}<\frac{0{,}25r(k_{Mix}-1)C_{Peff}}{0{,}25r(k_{Avgas}-1)C_{Peff}}(1+4\alpha) \tag{24}$$

$$\frac{k_{Mix}-1}{k_{Avgas}-1}(1-4\alpha)<\frac{\Delta U_{Mix}}{\Delta U_{Avgas}}<\frac{k_{Mix}-1}{k_{Avgas}-1}(1+4\alpha) \tag{25}$$

Here is assumed that $\alpha \ll 1$ and $U_{out,1}$ is close to $U_{out,2}$ (actually $U_{out,2}$ is, when tank is full, 33% less than $U_{out,1}$, but here is still considered close), and worst case relative error is for more precise consideration about ±3.5 α.
Dielectric constants for various Avgas and Jet Fuel A1 fuel mixtures, ratio k_{Mix}-1 / k_{Avgas}-1 (and hence ΔU_{Mix} / ΔU_{Avgas}) with minimal required accuracy class for fuel senders to detect the ratio for particular fuel mixture (using ±4 α error) are presented in ***Table 2***.

Table 2 *Dielectric constants for various Avgas and Jet Fuel A1 fuel mixtures, ratio* k_{Mix}*-1 /* k_{Avgas}*-1 and minimal required accuracy class for fuel senders to detect ratio for a particular fuel mixture*

Fuel volume mixture		*Dielectric constant (20° C)*	*k_{Mix}-1 / k_{Avgas}-1*	*Required accuracy class for fuel senders (% precision accuracy)*
Avgas (%)	*Jet Fuel A1 (%)*			
100	*0*	*1,9600*	*1*	
95	*5*	*1,9685*	*1,0089*	*0,2*
94	*6 (FAA tolerance)**	*1,9702*	*1,0106*	*0,2*
90	*10*	*1,9770*	*1,0177*	*0,2*
80	*20*	*1,9940*	*1,0354*	*0,5*
70	*30*	*2,0110*	*1,0531*	*1*
60	*40*	*2,0280*	*1,0708*	*1*
50	*50*	*2,0450*	*1,0885*	*2*
40	*60*	*2,0620*	*1,1063*	*2*
30	*70*	*2,0790*	*1,1240*	*2*
20	*80*	*2,0960*	*1,1417*	*2*
10	*90*	*2,1130*	*1,1594*	*2*
0	*100*	*2,1300*	*1,1791*	*2*

**max volume part of Jet Fuel in Avgas as suggested by tests performed by FAA (for real application please do check this data)*

4. DISCUSSION

As already mentioned there is just slight difference between the dielectric constant of correct fuel (Avgas) and the dielectric constant of improper fuel (mixture of Avgas and Jet fuel). Therefore method must be very sensitive to these subtle changes in dielectric constant. That requires quite precise capacitive fuel senders (accuracy class 0,2). However, such fuel senders are today commercially available under moderate price (few hundred USD), particularly when considering application. Capacitive probe diameter should be large enough (25 mm) to allow fuel mixing not just within a tank but also within the fuel probes. Fuel probes span across most depth of the fuel tank and integrate dielectric constant of fuel at various levels within a tank, not just at one point (what could be achieved with e.g. small capacitive probe placed at the bottom of a tank). Due to inherent sensitivity to change of dielectric constant method may encounter problems if fueled with Avgas that contain some additives (i.e. slightly different variants of Avgas may available at different refueling locations). These changes in dielectric constant must be somehow known in advance. Method will easily detect fuel contaminated with water (water has high dielectric constant of around 80).

5. CONCLUSIONS

Proposed idea could be a valuable approach for detecting misfueling of general aviation aircraft. It could be simple integrated into existing airplanes, replacing the old (unreliable) type of floating fuel sender. By employing two commercially available high precision offseted (displaced) fuel senders with temperature compensation it detects misfueling by detecting a change in dielectric constant of the fuel. Fuel senders are submerged into fuel to different depths and hence give different output voltages. The difference between these voltages is constant regardless of the fuel level. In case of msifuelling this difference shifts from its usual narrow range of values. Use of two fuel senders also gives redundant setup for measuring fuel level within a tank. This paper is just theoretical basis, for the real application extensive experiments would be needed, including process of initial mixing of fuels, influences of various fuel levels in the tank (e.g. full tank, three quarters and half tank) after misfueling, influences of fuel additives, effect of filling the fuel probes from the bottom and diffusion of fuel mixture within the probe (need for the sufficient probe diameter).

6. REFERENCES

1. AOPA Safety Brief No 4: Misfueling, http://www.aopa.org/asf/publications/SB04.pdf (PDF, accessed October 9, 2011)
2. Roy Langton, Chuck Clark, Martin Hewitt, Aircraft Fuel Systems, Wiley 2009, UK
3. Shenzhen, High accuracy capacitive fuel sensor, http://joint-tracking.com/Upload/PicFiles/2010.7.20_9.28.8_9083.pdf (PDF, accessed October 9, 2011)