Investigation of charge dissipation in jet fuel in a dielectric fuel tank

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Abstract. The electrostatic charge dissipation process in jet fuel in a polypropylene tank was investigated experimentally. Groundable metallic terminals were installed in the tank walls to accelerate the dissipation process. Several sensors and an electrometer with a current measuring range from $10^{-11}$ to $10^{-3}$ A were specifically designed to study the dissipation rates. It was demonstrated that thanks to the sensors and the electrometer one can obtain reliable measurements of the dissipation rate and look at how it is influenced by the number and locations of the terminals. Conductivity of jet fuel and effective conductivity of the tank walls were investigated in addition. The experimental data agree well with the numerical simulation results obtained using COMSOL software package.

1. Introduction

The electrostatic fuel charging effect is extensively described both in theoretical [1] and practical [2, 3, 4, 5] terms. The relevance of dissipation studies is underpinned by broad use of polymers and composites in fuel tanks. This work focuses on experimental investigations of electrostatic charge dissipation in jet fuel in a tank made of a material which has much lower conductivity than fuel. In real environment, dissipation occurs as the charge escapes through the tank walls and through possible grounded points, such as the tank’s external metallic elements exposed to environment. An experimental set-up was specifically designed to simulate the dissipation process in TS-1 jet fuel in a polypropylene tank by modeling the effects of possible grounded contacts on the dissipation rate. The principal dissipation rate evaluation method consisted in measuring the discharge current using probes immersed in fuel. For the method to be effectively used, we had to design and manufacture an electrometer capable of measuring currents as low as $10^{-11}$ A. An extensive series of experiments was conducted which provided a good insight into the impact of the grounded terminals on the dissipation rate and the effects of the resistance of the fuel surface layers bordering on the probes on the dissipation rate measurement accuracy. The charge sign was proved to have virtually no effect on the dissipation rate.

The dissipation process was simulated using COMSOL software package. Specific experiments were performed to measure the exact values of the fuel (TS-1) and tank wall conductivities required for the mathematical modeling.
The datasheet conductivity of TS-1 with no electrostatic agent added is $4 \cdot 10^{-12}$ S/m, which was confirmed by the measurement taken by the specifically designed instrument. The datasheet polypropylene tank conductivity value is from $10^{-15}$ to $10^{-14}$ S/m, whereas the effective conductivity measured in the experiment has a much lower value: $2.6 \cdot 10^{-16}$ S/m. These data were used in the dissipation process simulation with the aid of COMSOL software package. The simulated dissipation rates correlate well with the experimental values.

2. Experimental investigation

2.1. Experimental set-up

The experimental set-up diagram is given in figure 1. Fuel was either pumped from Tank 3 to Tank 1 or flowed from Tank 2 to Tank 1 due to the difference in levels.

![Experimental set-up block diagram](image)

**Figure 1.** Experimental set-up block diagram: ADC – analog-digital converter block; CSP – charge-sensitive pre-amplifier; HV – high-voltage source; K1, K2 – ground terminals; FM – fuel flow meter; BPV – bypass pump valve.

The key element of the experimental set-up is a polypropylene tank with a volume $V=0.48$ m$^3$ (1200x800x500 mm) and a wall thickness of 10 mm (Tank 1). The tank has a polypropylene cover and the entire system is shielded by a grounded 3 mm thick steel sheet. The tank is fitted with eight groundable metallic contacts located on the walls and bottom and eight discharge current sensors. The cylinder-shaped current sensors are made of brass and have a diameter of 9 mm and a length of 10 mm. The sensors are connected to the discharge current meter (electrometer) by bronze conductors insulated from fuel and can be moved heightwise allowing the discharge current measurements to be taken at different distances from the tank bottom. The fuel column height was equal to 420 mm and the ullage was blown with nitrogen.

The fuel pipeline downstream of the valve 3 is made of polypropylene except for a copper section where high voltage is supplied to the fuel from an external voltage source. Groundable terminals (K1, K2, ..., K8) are installed in the tank walls to control the dissipation rate. Charged fuel is supplied through the valve 9 into the tank containing discharge current sensors and charge-sensitive pre-amplifiers (CSP). The CSP output signal is transmitted to the analog-digital converter and saved by the PC. The discharge
current measurement system is described in more detail below. Once the experiment was over and the
discharge current dropped by over 10 times, the fuel was discharged into Tank 3. The duration of the
experiments varied from 1.5 to 25 hours depending on the number of grounded contacts. Besides,
measurements were taken to register fuel temperature, nitrogen pressure in the ullage, fuel flow rate
during tank filling, sensor depth and overall fuel level in the tank. A total of 11 series comprising 74
experiments were performed.

2.2. Discharge current measurement procedure

The charge-sensitive pre-amplifier converts the charge picked by the probe into a potential signal
registered by the set-up’s measurement system. The current running from the probe through the pre-
amplifier should be much lower compared to typical currents in the system under study. In the pre-
amplifier designed for the experiments and illustrated in figure 2, the measurement current was
determined by the input bypass $R_C$ (1 GOhm) and leakage current in the instrumentation amplifier
INA116 ($3 \cdot 10^{-15}$ A). The amplifier’s input circuits are provided with filters ($R_s C_F$) and gas dischargers
$R_A$ to ensure protection against high voltage.

![Figure 2. One channel of the charge-sensitive pre-amplifier.](image)

Designed as a 9-channel instrument, the amplifier has sensitive input circuits attached to
carbohydrate dielectric stands by point-to-point wiring. Each channel has a gain selector (1, 10, 100
and 1000). Each of the pre-amplifier’s channels was calibrated using a specifically designed testbed.
The calibration was performed in three input current ranges: $10^{-11}$ A, $10^{-10}$ A, and $10^{-9}$ A. Reciprocal
influence of the different pre-amplifier channels was investigated in the course of calibration. The
calibration curves demonstrated good linearity (0.1%) in all the input current and gain ranges.

2.3. Charge dissipation rate: experimental investigation results and their processing

Obtained as a result of the measurements was the dependency of the charge picked by the sensor from
the time elapsed after the tank had been filled with fuel charged by a high-voltage source. The
experimental data were processed by a dedicated software using ROOT software package [6]. A typical
view of the dependency for one of the experiments is shown in figure 3.
Figure 3. Charge dissipation in the experiment with a single sensor and no grounded contacts.

The problem of charge dissipation time profile in unlimited uniform medium was solved for a general case [1, 2]. Simultaneously solving the continuity equation and the field equations enabled describing the charge dissipation in the following form:

\[ \rho(r, t) = \rho_0(r, 0) \cdot e^{-t/\tau}, \tau = \epsilon \cdot \epsilon_0 / \sigma. \]  

(1)

Here \( \rho(r, t) \) is charge density, \( \rho_0(r, 0) \) is the charge density at the initial time point, \( \epsilon \) is the relative dielectric permittivity of the material, \( \epsilon_0 = 8.8542 \times 10^{-12} \text{ C}^2/(\text{N} \cdot \text{m}^2) \) is the absolute dielectric permittivity of vacuum, \( \sigma \) is the specific electric conductivity of the medium, \( t \) is time, and \( \tau \) is the charge dissipation time.

In the experiment, the charge dissipates in a big although not infinite volume limited by the tank walls with electric conductivity \( \sigma_{\text{wall}} \) from \( 10^{-15} \) to \( 10^{-14} \text{ S/m} \). Therefore, the dissipation process was described using the same type of dependency (1) whereas the dissipation time was found by approximating the experimental data. Figure 3 depicts the results of the approximation which yielded a dissipation time of \( 17175.9 \pm 0.9 \text{ s} \) in the absence of grounded terminals and with only one measurement probe used.

The probe has little effect on the dissipation rate for the walls with conductivity from \( 10^{-15} \) to \( 10^{-14} \text{ S/m} \) due to high resistance of the fuel layer bordering on the small-sized probe. In the case of a \( \varnothing 9 \text{ mm} \) probe, the fuel resistance grows fast reaching \( 3.4 \text{ TOhm} \), which is comparable to the resistance of the walls with conductivity of \( 10^{-15} \text{ S/m} \). The experiments with one, two and eight probes enabled evaluating the effective electric conductivity of the tank’s polypropylene walls: \( \sigma_{\text{eff}} = 2.637 \times 10^{-16} \text{ S/m} \) is the level at which the probe has a noticeable effect on the dissipation rate. However, even such a strong effect can be neutralized by selecting a smaller probe. The fuel layer around the probe of a length of \( 5 \text{ mm} \) and the diameter of \( 2.5 \text{ mm} \) has resistance of \( 6.4 \text{ TOhm} \). Besides, if grounded terminals are connected, the dissipation rate is governed by their low resistance. Thus, the small probes are quite suitable for measuring dissipation rates in the experiment described here.

As suggested by figure 4a, increasing the number of terminals can significantly reduce the dissipation time. Moreover, measurements taken at different levels do not differ by more than 12%. Obviously, the charge is distributed over the fuel volume in a fairly uniform manner provided that \( \sigma_{\text{fuel}} \gg \sigma_{\text{wall}} \).
Figure 4. Effect of the number of grounded terminals on the dissipation rate. Two heights above the tank bottom: $h_2=250$ mm and $h_3=20$ mm (a). Two probes of different sizes (b).

In the absence of grounded terminals, the dissipation rates obtained from measurements with different probes differ significantly (figure 4b), because the charge dissipates both through the tank walls and the probes. With three or more grounded terminals, measurements taken with probes of different sizes yield virtually the same results.

3. Numerical simulation of the charge dissipation process in TS-1 in a polypropylene tank

The electrostatic charge dissipation process in TS-1 was simulated using COMSOL software package. The simulation model was designed so as to describe the experiment conditions as precisely as possible. The simulation model and the experiments alike used 8 cylindrical terminals placed on the tank walls and connectable to zero potential. Eight current probes were immersed in fuel. They could be connected to zero potential through the designated resistance. The tank’s outer surface was grounded. The simulation model contained 48 charge volume density and potential measurement points corresponding to eight measurement probes placed at six different heights in the experiment.

The problem was solved in two steps. A simulation began with an electrostatic case with uniform charge volume density in fuel. The initial charge volume density was calculated based on the measurements of the current $I$ taken during fuel charging, tank filling time $\tau$ and fuel volume $V$:

$$\rho_v = \frac{I \cdot \tau}{V} = \frac{2 \cdot 10^{-6} \cdot 1.2 \cdot 10^9}{0.5} = 4.8 \cdot 10^{-3} \text{ C/m}^3.$$

The resulting potential distribution was used as the initial condition for solving the non-stationary dissipation case. The boundary conditions were the same as for the stationary case addressed at the first step: the tank’s outer surfaces were grounded and the grounded terminals had the required configuration. Besides, the current probes’ resistance was specified for the non-stationary case. Similarly to the experimental data, the numerical simulation results were saved to a text file and processed by a dedicated software using ROOT package [6].

Figure 5 compares the simulated dissipation rate to that obtained in the experimental series 2-5 with varied probe depths and external high voltage sign and an increase in the number of grounded terminals. The experimental points obtained in different experimental series are slightly shifted along the abscissa axis for the different series not to overlap. As indicated by figure 5, the differences in dissipation rates for all the series concerned lie within the same range (from 5 to 12%) as in the second series.
Figure 5. Comparison between series 2-5 and numerical simulation.

Thus the comparison shows that the experimental and simulated results differ by 12% maximum at room temperature. Smaller sensors display a bigger difference which is likely to be caused by the liquid moving in the experiment and unmoving in the simulation. It was noted in the experiments that the change in the fuel charge sign has little effect on the dissipation time. The location of a grounded terminal on the tank wall was demonstrated to have almost no effect on the dissipation rate.

4. Conclusion
Influence of the grounded metallic terminals on the charge dissipation process was investigated experimentally. Conductivity of jet fuel and effective conductivity of the tank walls were investigated in addition. It was shown that charge dissipation rate could be reliably measured using the charge-sensitive pre-amplifier. The experiments show that charge dissipation time exponentially decrease with increasing of the number of grounded terminals. The experimental data agree well with the numerical simulation results obtained using COMSOL software package.

References
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