Understanding electrostatic charge behaviour in aircraft fuel systems

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Abstract. This paper presents work on the simulation of electrostatic charge build-up and decay in aircraft fuel systems. A model (EC-Flow) has been developed by BAE Systems under contract to Airbus, to allow the user to assess the effects of changes in design or in refuel conditions. Some of the principles behind the model are outlined. The model allows for a range of system components, including metallic and non-metallic pipes, valves, filters, junctions, bends and orifices. A purpose-built experimental rig was built at the Health and Safety Laboratory in Buxton, UK, to provide comparison data. The rig comprises a fuel delivery system, a test section where different components may be introduced into the system, and a Faraday Pail for measuring generated charge. Diagnostics include wall currents, charge densities and pressure losses. This paper shows sample results from the fitting of model predictions to measurement data and shows how analysis may be used to explain some of the observed trends.

1. Introduction

An understanding of electrostatic charge in fuel systems is of interest to several industries, as it is possible that sufficient charge may be developed to lead to unwanted dielectric breakdowns. Although the topic of electrostatic discharge in fuel tanks has been studied for many decades there has been little work performed on developing models for electrostatic charge build up in the fuel prior to reaching a tank. Work has been primarily experimental or empirical. A motivation for the model presented here is to improve the understanding of measurement data at a more fundamental level. A further motivation is to provide a versatile software tool that can be used to predict the effects on charge generation of design changes, new materials or fuels, or modified refuel conditions.

Some of the theory used in the model, which is based on electrical double layer (EDL) theory, is outlined. The principles behind the measurement rig are then presented. Model data is fitted to measurement data, for a range of fuels flowing in straight pipes. This provides insight into why the charging tendencies of different fuels can be strongly dependent on fuel type.

2. Principles behind the model

Electrostatic charge build up as liquids flow through pipes has been studied for many decades, experimentally and theoretically. Some models are based on semi-empirical relationships derived from

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measurements (see for example [1], [2]). This approach makes it difficult to extrapolate to conditions outside those used to derive the model.

More rigorous modelling, based on EDL theory, has been performed (see, for example, [3], [4]). Positive and negative ions are assumed to be present in the liquid, arising from the dissociation of ionic impurities or additives. Ions of both sign react with the pipe wall. Ions of one sign are preferentially adsorbed onto the wall, forming a layer attached to the wall. Ions of opposite sign form a ‘diffuse layer’ that extends some distance from the wall. If the liquid were not moving then ions would remain in these layers. When the liquid is moving then the ions in the diffuse layer will be entrained in the flow and travel down the pipe with the liquid.

The details of the modelling are dependent on the further assumptions that are made. In our model we assume that the ‘small charge density’ approximation is valid. This requires that the concentration of the excess ions is ‘small’ such that the imbalance in the concentrations of positive and negative ions is a small perturbation on these concentrations. We also assume that the flow in aircraft fuel pipes and other fuel systems components is turbulent. With these assumptions the charge density in a pipe is given by [5], [6], [7]:

$$\bar{q}(x) = q_w \left( \frac{R_{\tau_w}}{\rho \bar{v}^2} \left( \frac{\lambda}{a} \right)^2 \right) \left[ 1 - \delta/\lambda \sinh \left( \frac{\delta}{\lambda} \right) \right] + \frac{\delta}{\lambda} \left( \frac{1}{1 + a \delta \lambda^2} \right) \left[ 1 - \exp \left( -\frac{x}{L_D} \right) \right] + q_0 \exp \left( -\frac{x}{L_D} \right)$$

$$+ B(\bar{q}_0 - \bar{q}_\infty) \left[ \frac{1 - \exp \left( -\frac{x}{L_D} \right) \left( -\frac{x}{L_D} \right)}{\exp \left( -\frac{x}{L_D} \right)} \right]$$

(1)

where $\bar{q}(x)$ is the charge per unit volume, averaged over the pipe cross section, at a distance $x$ from the pipe inlet. The parameters are: $a$ is the pipe radius, $\rho$ is the fluid density, $\bar{v}$ is the fluid velocity, averaged over the pipe cross-section, $R$ is the Reynolds’ number $\left( = \frac{2 \rho \bar{v} a}{\mu} \right)$, with $\mu$ the fluid viscosity, $\tau_w$ is the shear stress at the wall, given by [6] $\tau_w = 0.0396 R^{-1/4} \rho \bar{v}^2$, $\delta$ is the laminar sub-layer thickness, ie the radial distance from the pipe wall over which the flow is laminar, given by [6]:

$$\delta = 13 \left( \frac{\tau_w}{\rho} \right)^{1/2} \left( \frac{1}{S} \right)^{1/2} \left( S = \frac{v}{D}, \nu = \frac{\mu}{\rho} \right)$$

(2)

where $S$ is the Schmidt number and $\nu$ is the kinematic viscosity. The quantity $\lambda$ is the Debye length $= \left( \frac{\varepsilon D}{\sigma} \right)^{1/2}$, where $\varepsilon$ is the fluid’s permittivity, $D$ is the average diffusion coefficient, or diffusivity, of the ionic species in the fluid, and $\sigma$ is the fluid’s electrical conductivity. The Debye length determines the radial distance from the pipe wall that the ions are present in the electrical double layer. The quantity $q_w$, the equilibrium wall charge density, is the density of ions at the wall that forms when the charging and relaxation processes are balanced. This only occurs in a pipe of sufficient length. The quantity $x$ is the distance that the fluid has travelled down the pipe from the entrance, $L_D$ is the charge ‘development length’, the distance that the fuel flows in the pipe before the equilibrium wall charge is set up. This is given by:

$$L_D = \frac{\varepsilon \bar{v}}{\sigma(1 + \frac{2\lambda^2}{\delta a})}$$

(3)

The quantity $\bar{q}_0$ is the average charge density at the start of the pipe and $\bar{q}_\infty$ is the average charge density in an ‘infinite’ pipe. When the pipe diameter is much larger than the Debye length, which is the regime in which we are interested for aircraft fuel system applications, the equilibrium wall charge
is given by \[ q_w = -\frac{\sigma \zeta}{D}, \]
where \( \zeta \) is the zeta potential (see, for example, [6], [8],[12]). \( B \) is the ratio of the conductance per unit length of the fuel to the conductance per unit length of the fuel and pipe wall. \( B=0 \) corresponds to a metallic pipe, \( B=1 \) to a perfectly insulating pipe.

Other fuel system components are incorporated into the model. Micropore filters are modelled using the theory of Huber and Sonin [9],[10], taking account of charge relaxation with the theory of Washabaugh and Zahn [11]. Components such as valves, bends and junctions are modelled in terms of pressure drop [12]. The effects of temperature are incorporated into the model through a range of analytical expressions gathered from the literature. Details will be the subject of a separate paper.

3. Measurement rig
A purpose-built test rig was built at the Health and Safety Laboratory (HSL) in Buxton UK. The rig comprises; a controlled fuel delivery system operating at up to 150 m\(^3\)/hr, a test section where different components may be introduced into the system, and a Faraday Pail for measuring the charge accumulated by the fuel. Measurements include wall currents, charge densities and pressure losses. Figure 1 shows a schematic of the rig.

![Schematic diagram of the test rig](image)

**Figure 1:** schematic diagram of the test rig.

4. Comparison of experimental data and model predictions
Predictions from the EC-Flow model have been fitted to measurement data, for a range of components and fuels. Fitting was carried out by varying the zeta potential and the ionic diffusivity. Sample results from the fitting are shown in figure 2. Fitted values (at 20°C) are: 35mV (3pS/m fuel) and 33mV (100pS/m fuel) for the zeta potentials and \( 10^{-9} \) m\(^2\)/s\(^{-1} \) (both fuels) for the diffusivities.

![Graphs showing measured and fitted variations of fuel charge density with flow velocity](image)

**Figure 2:** measured and fitted variations of fuel charge density with flow velocity, in metallic pipes of radius \(~31\)mm, for fuel conductivities of 3pS/m (left) and 100pS/m (right).
The very different trends seen in figure 2 for the two fuel conductivities (and for other fuel conductivities not shown here) are understandable when we consider the competing effects that arise as the flow velocity increases. The pipe becomes shorter relative to the charge development length, so less charge may build up. However, the laminar sub-layer thickness decreases so that more charge may be entrained in the flowing fuel. The balance between these competing effects depends on the ratio of the pipe length to the charge development length and on the ratio of the Debye length to the laminar sub-layer thickness. Figure 3 shows the variation with flow velocity of the ratio of the pipe length to the charge development length (solid curves) and the ratio of the Debye length to the laminar sub-layer thickness (dashed curves), for two conductivities. The competing effects are apparent, as are the different regimes for the different conductivities.

![Figure 3: variations with flow velocity of the ratio of the pipe length to the charge development length (solid curves) and the ratio of the Debye length to the laminar sub-layer thickness (dashed curves), for two fuel conductivities (3 and 100pS/m).](image)

5. Summary
A model for charge generation in fuel systems has been developed and an experimental test rig has been built and used to provide comparison data. The model helps understand measured trends in charging behaviours. This has been demonstrated for a simple component (a metal pipe) and for two fuels with different conductivities. A broader range of components, and other fuel types, can be used in the model. The model is useful to help identify primary sources of electrostatic charging, and to examine methods to mitigate against unwanted charging.

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