Journal of Electrostatics 71 (2013) 1111–1116

Contents lists available at ScienceDirect

Journal of Electrostatics

journal homepage: www.elsevier.com/locate/elstat

Transient electric charging of dielectric liquids in recirculation systems

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ARTICLE INFO

Article history:
Received 4 January 2013
Received in revised form
8 August 2013
Accepted 29 September 2013
Available online 27 October 2013

Keywords:
Voltage spike
Electrostatic
Engines
Filters
Lubricating oils

ABSTRACT

This paper describes a transient electric charging phenomenon due to flow-induced electrification during a cold startup of dielectric liquids in a recirculation system. This transitory effect exhibits itself as a static voltage spike in the system. It is argued that simultaneous rise in the liquid temperature and the circulation flow rate can generate conditions for such electrostatic voltage spikes to exist. These spikes have been verified experimentally in the laboratory and we report qualitative agreements between the reported experimental data and the theoretical considerations. With a cold start, this transient charging has the potential to induce a large static voltage and large space charge in the circulating system that can damage other components.

1. Introduction

Electrification of dielectric liquids in motion is caused by charge separation at the interfacial boundary between the moving liquid and the containing wall. Virtually all liquids have some electrical conductivity which is the result of existence of some ionized species in the liquids. The equilibrium condition between the charged species and a bounding interface generally induces a finite charge in the fluid adjacent to the interface resulting in a convective current when the flow takes place. For dielectric liquids with very low conductivity, this effect is magnified as the corresponding Debye length becomes comparable to other length scales of the flow.

This charging convection is known to be a source of numerous industrial hazards, primarily in the petroleum and power industries [1–5]. This effect occurs in systems with the flow of low-conductivity liquids such as purified fuels, lubricating oils and other hydrocarbon liquids when those systems aren't properly grounded. In practice, however, these hazards exhibit themselves mostly as an infrequent electric breakdown in some portion of the system. The incidence of electrical breakdown for a given system most often depends on a number of inter-related parameters such as the ambient air temperature and humidity [6], in addition to other factors including, but not limited to, the geometries of the system and its components, the flow condition and the electrochemical properties of the fluid–solid interfaces at various parts of the system. Accordingly, even when a system in operation is prone to an electrostatic discharge, there may not be sufficient conditions for an electrical breakdown and in practice the incidents occur infrequently with such an irregularity that they remain undetected.

A number of analytical and laboratory studies have characterized this flow charging phenomenon under steady state conditions [2–5]. These studies have in general successfully demonstrated the physicochemical parameters that determines the resulting electric current for a dielectric liquid in a given flow geometry. However, unsteady charging under different flow conditions have not been studied as widely. Transient charge accumulation during fuel loading in a tank with the charged fluid entering as a jet has been studied [7,8]. Two-dimensional numerical calculations of transient electrification in a rectangular channel when the flow starts from zero and the fluid is electrically neutral at the entrance of the channel has also been provided previously [9]. The present study considers the transient electrification in a recirculating flow of a low-conductivity liquid where there is a simultaneous change in the flow rate and the operating temperature of the system.

Circulation of dielectric liquids is vital to virtually all power systems because of its tribological properties. The circulating unit of a system features common components such as a micro-filter and a pump, among other parts, that can potentially induce enhanced electric charging in the liquid. Electric charging by the filter and the pump can often be orders of magnitude larger than the streaming current induced by the connecting pipes and

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http://dx.doi.org/10.1016/j.elstat.2013.09.009

conduits. During normal steady state operation of a power unit, the circulation of the dielectric liquids is used to cool its internal parts and as a result, the electrical conductivity of the fluid is high enough that any induced electric current in the moving liquid will dissipate quickly with minimal effect to other components.

At a cold start of a power unit, its circulating oil temperature and flow rate steadily rise until the operating conditions are reached. The initial temperature increase is due to viscous heating and heat input from other components in the system. This temperature rise in the start-up stage affects the stream electrification in several ways. It reduces the viscosity of the circulating fluid and the pressure difference that the driving pump in the circulation system experiences and in turn gives rise to a continuous increase in the flow rate in the start-up stage. A rise of the temperature also increases the electrical conductivity of the liquid and accordingly the streaming electric current will be time dependent. It also influences the electrokinetic effect at the solid–liquid boundary where charge separation takes place. This paper explores how a temperature rise in the system can contribute to production of a static electric spike in some section of the circulation system.

2. Assumptions and equations

The presence of space charge in a dielectric liquid is due to an imbalance between positive and negative ionic species in the liquid. In the limit of small charge density $|q| \ll Fc_o$, with q being the charge density, F the Faraday's constant and c_o the concentration of positive and negative ions in the electrically neutral state. With this assumption, liquid charging will have a negligible effect on the electrical conductivity of the liquid κ that can be expressed by $\kappa = 2Fc_ou$, where u is the average mobility of the ions. The mobility of ions is strongly temperature dependent and the fluid conductivity will then be temperature dependent. Accordingly, it will be assumed that the fluid conductivity is independent of charging in the liquid and its temperature effects can be expressed by the correlation [10]

$$\kappa = \kappa_o e^{\frac{-E_o}{k_B(T-T_o)}} \tag{1}$$

where κ_o is fluid conductivity at the reference temperature T_o, T the temperature, E_o is the reference thermal activation energy of the charged-species and k_B the Boltzmann constant. The empirical constants E_o and T_o in this equation are not arbitrary and their values for a given liquid can be independently determined from the corresponding viscosity measurements. T_o is a glass-transition temperature of the liquid at which point the liquid has zero fluidity and ionic mobility. Eq. (1) is derived with the assumption that, for a given liquid, the product of the conductivity and viscosity at different temperatures is constant and independent of temperature [10].

In the small charge density approximation, the charge transport equation for an incompressible liquid has the form

$$\frac{\partial q}{\partial t} + V \cdot \nabla q - D\nabla^2 q + \frac{\kappa q}{\varepsilon} = 0 \tag{2}$$

where V is the fluid's bulk velocity vector, D the average molecular diffusion coefficient of the ions and ε the liquid's electrical permittivity. This equation is linear in q, even when V and κ are time dependent and the superposition principle will be valid to study unsteady charge convection. For a recirculation system, there can be multiple sources of charge generation into the liquid and applying the superposition principle becomes critical in isolating the charging effect of a component in a complex system.

Generation of electric current in flow streams is a primarily an interfacial phenomenon between a low-conductivity moving liquid and a solid surface. Depending on the nature of solid surface, the mechanism of liquid charging is speculated to be electron tunneling in case of conducting surfaces (metals) or ionic selective adsorption in case of non-conducting surfaces (e.g. plastics), or a combination of the two. The transfer mechanism at the interface by-and-large determines the charge polarity. However, despite decades of experimental and theoretical work in this area, the exact nature of interfacial charging remains unknown. In the past decade, there have been efforts to quantify interfacial charging for a number of dielectric liquid-wall combinations, but these works, while valuable, lack any robust predictions for the charge polarity or its concentration at the interface [5].

In most instances when some ionic species are present in the dielectric liquid, electron tunneling at the metal interface will induce a negative charge in the liquid and ionic selective adsorption of an organic interface will generate a positive charge in the liquid for most of the systems. Accordingly, when the surfaces are present electric charging of a non-organic interface will neutralize some of the charging effects by an organic interface when a steady state has been reached. The principal components of a power circulation system are shown schematically in Fig. 1. Accordingly, if the components such as the pump, heat exchanger and connecting tubes are of inner metallic surfaces in contact with the circulating fluid, negative electric current will be induced in the system. On the other hand, most of the filters are of organic materials and the resultant electric current will be positive for majority of dielectric liquids; however, there are instances that the filter-liquid system can induce negative charge in the liquid [11].

The present analysis uses a one-dimensional unsteady approach where the liquid has acquired electric charge at some upstream point in the circulation system. Consequently, interfacial charging effects of the connecting tubes will be neglected. The most dominant charging source will be the filtration system in the circulation that often utilizes a micro-filter. Electric charging in the filtration of dielectric liquids depends on a number of physical factors, such as the apparent fluid velocity, filter thickness and porosity, pore size and the fluid electrical conductivity, among others [12]. The parameter q_f will be taken as the uniform space charge density of the liquid exiting the filter. Note that to study transient effects, q_f is needed to be expresses in terms of the liquid temperature, which to the knowledge of the authors don't exist in the literature. When filter pore sizes are of micron size, for most of the power systems, one may assume that the space charging has reached its limiting value. This limiting value depends on the ionic concentration in the fluid c_o as well as the ionic mobility u. Accordingly, as an ad-hoc assumption, the present study assumes that q_f will be proportional of the electrical conductivity of an insulating liquid,

$$q_f = \alpha_f \kappa, \tag{3}$$

where α_f is solely a filter parameter and independent of other factors such as fluid velocity or temperature, at least in the charge-saturated limiting case. Eq. (3) then provides a condition for transient fluid charging at the point source as the operating temperature varies.

For a one-dimensional unsteady charging effect, eliminating the diffusion term, Eq. (2) can be simplified to

$$\frac{\partial q}{\partial t} + U(t,s)\frac{\partial q}{\partial s} + \frac{\kappa(t,s)q}{\varepsilon} = 0, \tag{4}$$

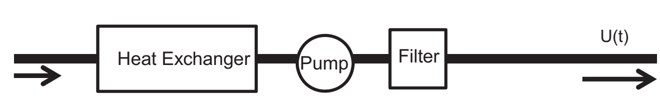

Fig. 1. Schematic diagram of a circulation system with common components.