UNIVERSITI MALAYSIA SARAWAK
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Faculty of Engineering

DROPLET CHARGE ESTIMATES FROM CHARGE AND MASS FLUX DATA

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Bachelor of Engineering with Honours
(Mechanical Engineering and Manufacturing Systems)
2005

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This project is submitted in partial fulfillment of
the requirements for the degree of Bachelor of Engineering with Honours
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The project report attached here to, entitled "***Droplet Charge Estimates From Charge And Mass Flux Data***" prepared and submitted by ***PL. YASSLIN ASSIN @ SALIHIN B YASSIN*** in partial fulfillment of the requirement for Bachelor of Engineering with Honours in Mechanical Engineering and Manufacturing System is hereby read and approved by:

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Supervisor

14·05·05

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Dedicated to my beloved family and friends

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ABSTRACT

The main objective of this project is to calculate the droplet's charge which radial trajectory paths is generally governed by its charge-to-mass ratio. The analysis of the droplet charge as a function of droplet diameter, spray current and atomizer boundary is necessary in order to model and predict the charged spray plume shape computationally. A commercially available software MATLAB, was used to calculate the droplet charge and Rayleigh limit ratio. The droplet charge increase with decreasing droplet diameter. The droplet velocity is reduced as droplet diameter reduced and well dispersed. These results show that the knowledge of droplet charge as a function of droplet diameter that can be utilized for optimum atomization process. The droplets charge was found to be less than the Rayleigh limit.

ABSTRAK

Tujuan projek ini adalah untuk menghitung arus tenaga pada titisan air (Charged droplets) yang pada kebiasaannya mempunyai jejarian arah dimana ini dikawal oleh purata arus tenaga dan jisim bagi sesuatu cecair. Analisis pada ‘Droplet charge’ adalah penting sebagai fungsi mengkelasifikasikan diameter titisan cecair dan lingkungan semburan (Spray) untuk merekabentuk model. Penggiraan ini menggunakan ‘Matlab Program’ bagi mendapatkan ‘Droplet charge’ dan nisbah limit bagi ‘Rayleigh’. Peningkatan ‘Droplet charge’ akan memberi kesan terhadap penurunan ‘Droplet diameter’. Kelajuan pancutan ‘Droplet’ berkurangan apabila ‘Droplet diameter’ menunjukkan pengurangannya tetapi agak baik dari segi penyebaran ‘Droplet’. Keputusan ini menunjukkan pengetahuan ‘Droplet charge’ penting bagi memberi kesan terhadap ‘Droplet diameter’ untuk digunakan dalam proses kawalan penyebaran secara optimum. Keputusan juga menunjukkan bahawa ‘Droplet charge’ adalah dalam lingkungan ‘Rayleigh limit’ ataupun dibawah parasnya.

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NOMENCLATURES

Symbol	Description	Unit
Q	Charge	C
D	Droplet diameter	μm
v	Velocity	m/s
C_D	Drag coefficient	-
E	Electric field	v/m
Re	Reynolds number	-
ρ	Density	kg/m^3
I	Current	A
m	Mass	kg
$\dot{m}$	Mass flow rate	kg/s
u	Axial velocity	m/s
μ	Viscosity	Lg/ms
τ	Torque	Nm
F	Force	N

Subscript

Symbol	Description
n	No. of droplet
r	The r^{th} annulus
inj	Injection
s	Spray
g	Gas

Chapter 1

1.1 Introduction

Nowadays we have seen many industrial applications that require optimization of charged polydisperse sprays, such as car painting and pesticide sprayers. Atomization is the term used to denote the transformation of bulk liquid into sprays and other physical dispersions of small particles in gaseous atmosphere. Dombrowski and Mundy (1968) describes the conditions of good atomization as the most effective way of utilizing the energy imparted to the liquid that the liquid has a large specific surface before it commences to break down into drops. Thus, the primary function of the atomizer is to transpose bulk liquid into thin sheets.

In considering the creation of drops it is instructive to examine the simplest case, which is a flow through a cylindrical orifice. Sheet break up is of primarily interest. However, jets break up need to be considered as they are used as an atomization source in their own right as well as occurring as the intermediate stage in the sheet route. At the lowest flow rates there is simple dripping. A drop forms and when its weight is enough to overcome the retaining surface tension force it breaks away. Increase of the liquid flow rate results in the behaviors.

1.2 Motivation of the study

For the liquid fuel in a combustion chamber where release of unburned hydrocarbons may occur, problems such as the engine running at medium speed and unclean area of the piston engine are undesired. Upon injection of the liquid fuel into a combustion chamber, the liquid undergoes atomization, which causes the liquid to break up into a large number of droplets of various sizes and velocities.

Older diesel engines mix the fuel with air by means of a precombustion chamber with high turbulent flows. The smooth running of these engines is paid by the reduced efficiency due to the additional friction losses in the precombustion chamber. Modern diesel propulsion concepts are driven by a direct injection (DI) engine. Here, the fuel is injected directly into the combustion chamber and mixing with the combustion air takes place in the cylinder.

The combustion of a four-stroke engine can be divided into intake, compression, expansion and discharge. In diesel-type combustion, three additional factors enter into the combustion phenomena. First, the ignition delay (the time between start of fuel injection and first combustion) depends on the rate of heating, formation of a combustible mixture, and the mixture chemical kinetics. Second, the high pressures encountered may cause the droplets to approach their critical points, thus causing droplet breakup and a shift in the vaporization and burning rates. Third, in some engines (and some oil burners as well) residual fuels are used which may break down (crack) in the liquid droplet phase, causing different burning rates and the formation of residual carbon shells. Most important for the combustion is the air-fuel mixing before ignition. Here the spray performance is the main parameter for a clean and complete combustion. Namely the primary break-up, the mixture formation with secondary break-up and the chemical reaction define the efficiency and the composition of the exhaust gas.

The droplet dispersion is the primary importance which atomizers come in a large variety of designs and flow rates. Spray combustion is widely used because it gives a practical method of rapidly vaporizing and mixing liquid fuels with air. Size distributions for sprays are expressed by various empirical distributions function, which often used to characterize the injector. In such case like hazardous waste combustion which a fuel destruction efficiency will cause in decreasing of engine performances.

The dispersion of droplet influences the efficiencies of a combustion process. When the liquid fuel is injected into a combustion chamber, the liquid undergoes atomization, which causes the liquid to break up into a large number of droplets of various sizes and velocities. Diesel engines have a very dense spray in which droplet interactions and local cooling by vaporization are important. For small engines and for cold starting conditions in all engines, the spray typically hits the piston surface, causing droplets to wet the surface, which changes the vaporization and mixing mechanism. Finally, combustion in an enclosure such as an engine cylinder causes combustion-induced motion because of the expansion of products in various parts of the cylinder volume.

The nozzle type affects the spray formations. There are different types of spray nozzles resulting in the variation of the to droplet sizes occur. For a swirl-type nozzle, droplets, which are formed near the nozzle exit, may undergo further breakup due to aerodynamic forces. Large droplets deforms into a bag shape and then burst. For smaller droplets, the drop may vibrate and then separate into two or more parts. For such drops under condition of sudden change in relative velocity, there is a time delay period followed by shedding of very small droplets from the sides of the existing droplets. The shape of the shedding droplets at this point is elliptical at the forward surface and rather flats at the rear.

At the end of the spray formation region, one would like to know the droplet size, velocity, and number distributions, the air velocity, and number distributions, the air velocity and temperature, and the droplet temperatures. In some sprays the breakup region will overlap the vaporization region. To follow the process through the vaporization region, a model is needed for air motion including turbulence and the interaction of air and the interaction of air and droplet momentum. To follow droplet motion, droplet drag coefficients and droplet vaporization models are needed. Understanding the ignition process, both for the free vapor and the droplet boundary layer, is necessary in order that the onset of burning can be established. Then droplet burning rate relationships are needed. If emissions are to be predicted, models for the reaction kinetics are required. Radiation from carbon particles formed in the diffusion flames is an important component in the energy balances and in the diffusion flame temperature prediction. The convective heat losses may also play a role and are tied to the general problem of prediction of mixing, recirculation of products, and turbulence.

1.3 Objectives of the study

The objective of many spraying applications is to distribute liquid onto a selected target in a controlled and predetermined way. Electrostatic forces can be used to deflect charged drop trajectories, so that drop deposition onto a target can be controlled. For accurate targeting, not only is it essential for drops to be charged but also the magnitude of the charge must be controlled. In some situations, where targeting requirements are precise, as for example with ink-jet printing, drops are equi-sized and charge levels may be controlled with great accuracy. Spray painting is another controlled situation in which electrostatic spraying of earthed objects of well-defined geometries is used. Spray distance, angle, and charge levels can be adjusted for optimum coating.

There has been work done on manipulating electrohydrodynamic atomization to produce larger sheet effects of sprays, and the development of modeling techniques. The objectives of this study were:

1. To understand how the charge being produce
2. To understand charge droplet dynamics in electrospray ionization.
3. To estimate droplet charge as a function of droplet diameter

1.4 Literature Survey

1.4.1 Lord Rayleigh Theory

'Rayleigh Limit' (RL) states that if a liquid droplet is electrically charged (any sign), the charge resides on its surface. The repulsive coulomb force between the like charges tries to tear apart the droplet (www.physik.tu-ilmenau.de). This force is opposed by the surface tension that tries to keep the surface minimal, i.e. a spherical shape. Lord Rayleigh was able to perform a quantitative analysis of this situation in 1882 and he gave a formula, which relates the maximum charge a droplet can bear to its surface tension and radius. Lord Rayleigh predicted the jet formation for droplets that are charged well above the Rayleigh limit. An estimate for the charge in a droplet of radius r is given by the Rayleigh limit:

$$q^2 = 64\pi^2 \varepsilon r^3 \sigma \quad (1.1)$$

where ε is the permittivity of the medium surrounding the droplet.

1.4.2 Droplet size, velocity and flux density measurements

Many types of instrumentation and techniques may be used to measure drop size and their velocities. Today, some researcher such as Mulder and Hers (2000) use laser like Laser Doppler Anemometry (LDA) to determine these physical characteristics at the same time, as the drops are in-flight. From the lab@sprayresearch.com, research that the Phased Doppler Particle Analyzer [*PDPA]* advantage is that the spray can be characterized as to droplet size, velocity and flux density with a single series of measurements utilizing a single instrument. The accuracy of PDPA mass flux measurements is typically ±15%. The measurable particle concentration limit depends on particle size. In general, a much higher concentration of small particles can be tolerated than of large particles. Hui He Qiu and Chin Tsau Hsu (1999) works on Phased Doppler Anemometry (PDA) free from the measurements-volume effect where using PDA to measure the mass flux is the most accurate measurements of droplet size. Because PDA is based on single-particle dispersion theory.

Nilars, et al (2000) in investigating PMS (Particle Measuring System) and PDPA (Phase Doppler Particle Analyzer) how big the difference between two commonly used systems for droplet size measurements to define 40 sets of official reference agricultural nozzles. From the results show the problems of PDPA measurements with respect to the large droplets. Measurements with the PMS at Silsoe laboratory have indicated maximum droplets ranges for the reference nozzles of 450mm for the 11001, 600mm for the 11003, 700mm for the 12006 and 900mm for the 8008. Above these values the data can be discarded. The nozzles were measured spraying water only. They concluded that PDPA instruments are capable of producing huge amounts of useful and informative data, but it is also clear that no two independent systems may give similar results. In fact with the multitude of different settings for each piece of equipment, even the same machine might not give exactly the same absolute results when set up differently. In general, when measuring the reference nozzles with the two machines under investigation, the Aerometrics calculated smaller VMDs for the small nozzles and larger for the big nozzles, although this was not the case for the test nozzles. This confirms the need for reference nozzles when trying to classify sprays.

There have been only a few reported studies that have used pressure and mass flux probes to understand the behavior of electro-thermal thruster plumes. A study performed by the McDonnell Corporation in the 1960's focused on measuring impact pressure and mass flux measurements in the plume of several 30 kW class hydrogen arcjets . A more recent study by Penko, et al, (1991) examined the plume of a nitrogen resistojet with an impact pressure probe for verification of direct simulation Monte Carlo (DSMC) and Navier Stokes continuum models.

Hargus and Cappelli (1996) in investigating mass flux measurements in the plume of a low power arcjet nozzle, their efforts that combine both experimental and theoretical studies to build reliable models of arcjet performance that can be used as design tools for next generation thrusters. They're reported that, no mass flux measurements have been published on low power hydrogen arcjets. Therefore, a number of mass flux measurements were performed for both cold and arc heated flows in the plume of a low power arcjet. Their results were compared Analysis of the results the cold flow mass flux measurements indicate that the central core flow behaves as modeled. However, the flow in the wings of the mass flux profile is not being captured. The ability to only capture 50% of the total flow indicates that there is a problem of a serious nature in this measurement.

1.4.3 Charge and fission of droplets in electrostatic sprays

Gomez and Tang (1994) published charge and fission of droplets in electrostatic sprays. They measure of the charge and size of heptane droplets generated by electrostatic sprays showed that the droplet charge-to-volume ratio is a monotonically decreasing function of size. In the useful range of electrospray operation, characterized by droplets smaller than the size of the orifice from which the liquid is issued, it was found that the larger were the droplets the closer they were to the Rayleigh limit. In particular, when droplets had charging levels between 70% and 80% of such limit, they were observed to rupture because the repulsive force due to surface charge evidently overcame surface tension. The rupture phenomenon, here termed Coulomb fission, was also captured in microphotographs that typically showed a droplet with one or two, diametrically opposed, conical protrusions terminating in a fine jet ejecting a stream of much smaller, apparently equisized offsprings. The process appeared swift and, yet, well ordered, quite different from the common view of a violent, convulsive explosion. Corroborating evidence on the disruption pattern was also gathered by quantitative measurements of the evolution of the droplet size distribution in evaporating sprays using phase Doppler anemometry (PDA). Implications of these findings are finally discussed in the context of a particular application of electrostatic sprays, electrospray ionization, a technique that is revolutionizing the mass-spectrometric analysis of large biomolecules.

1.4.4 Charge-to-mass ratio

Droplets charge density or charge-to-mass ratio is the basic parameters that affect the electrohydrodynamic atomization characteristics. The droplet size decreases with increasing droplet charge density, atomization also known as an “electrospray” or “cone-jet” (Gemci et al, 2002). Method of droplet charging is similar to that working in the technology of ink-jet printing. The applications described by Orme et al. 2000, an ink-jet jet printer produces characters on paper by deflecting charged droplets on one axis while the print head moves along the perpendicular axis. The droplet charge and the strength of the electric field through which the droplet moves determine the amount of deflection achieved by a droplet. The net charge on the droplet is obtained at the time of droplet formation.

1.4.5 Electrohydrodynamic Spraying

Jaworek and Krupa (1995) published electrohydrodynamic (EHD) spraying of liquids is a physical process caused by the electric force applied to the surface of liquid. The electrical shear stress elongates the liquid meniscus formed at the outlet of a capillary, to the form of a cone and/or a jet, which next deforms and disrupts into droplets because of the electrical and mechanical forces. The droplets generated