

## **Chemical Methods for Decreasing Jet Fuel Flammability**

Heather D. Willauer<sup>1\*</sup>, Ramagopal Ananth<sup>1</sup>, John B. Hoover<sup>1</sup>, George W. Mushrush<sup>1,2</sup>, and Frederick W. Williams<sup>1</sup>, Naval Research Laboratory, Code 6180, Navy Technology Center for Safety and Survivability, 4555 Overlook Ave., SW Washington, DC 20375 <sup>2</sup>Department of Chemistry, George Mason University, Fairfax, VA 22030

\*Correspondence: Heather D. Willauer, Naval Research Laboratory, Code 6180, Navy Technology Center for Safety and Survivability, 4555 Overlook Ave., SW Washington, DC 20375, USA; Fax: 202-767-1716, E-mail: willauer@ccs.nrl.navy.mil.

## **ABSTRACT**

The most devastating aircraft fuel related fires occur when there is a catastrophic failure of an aircraft wing or jet fuel tank as a result of a ground crash. The cause of these intense fires is the rapid atomization of fuel that produces a highly flammable, extremely explosive fuel-air mixture in the presence of an ignition source, and it is these intense fires that greatly reduce post crash survivability.

In our efforts to develop fire safe fuels, a series of additives to jet fuel has been chosen that rely significantly on their chemical structure and composition to reduce fuel flammability by increasing droplet size during a wing tank failure. This presentation will discuss the methods utilized to evaluate the effect that specific chemical additives have on reducing the mist flammability characteristics of jet fuel and the influence of additive concentration on fuel drop size and fuel stability.

## INTRODUCTION

During the 1970's and 80's, physical methods were utilized by scientists to reduce fuel flammability in the event of a catastrophic fuel release. The fuel release scenarios of interest were those that occurred as a result of damage to an aircraft wing or jet fuel tank during a ground crash.<sup>1,2</sup> The rapid release of atomized fuel in the presence of an ignition source, during such an event, can produce intense fire and explosion hazards. Such hazards have been known to greatly reduce post crash survivability.<sup>1,2</sup>

The gelled fuel program<sup>1</sup> and the antimisting kerosene (AMK) program<sup>2-5</sup> were two programs sponsored by the Federal Aviation Administration (FAA) during this time. Both programs relied on high molecular weight polymers to increase fuel viscosity and thus inhibit fuel atomization. Small scale laboratory programs at the time showed great promise of success. However significant changes in fuel viscosity required major modifications to jet engines. In 1984 a Boeing 720 was utilized in a large scale controlled impact demonstration at NASA Dryden Flight Research Center. The demonstration results prompted the cancellation of major research efforts in this field.<sup>1</sup>

Previous research has shown that atomization of jet fuel can produce highly flammable, extremely explosive fuel air mixtures.<sup>1-6</sup> The flammability of the fuel air mixtures is dependent on the number density and droplet size of the fuel. Smaller droplets exhibit greater flammability characteristics.<sup>1</sup> One of our research objectives is to develop an understanding of the mechanisms that control aerosol production. This will enable the modeling of aerosol production mechanisms and the correlation of flammability characteristics with critical aerosol parameters. Such parameters include: liquid surface tension, liquid molecular interactions, viscosity, vapor pressure and liquid density.<sup>7-11</sup> A fundamental understanding of critical aerosol production will

provide insight into the types of chemical additives that will successfully reduce fuel flammability.

The nature of an additive and its physiochemical interactions with the fuel will be critical to its ability to reduce fuel flammability. This idea of non-flammable fuel is incongruous because the fuel needs to atomize and burn in the jet engine combustion process. Thus ideally, the additive chosen would not interfere with this process. This may be achieved by keeping additive concentrations low and utilizing the controlled environment of the jet engine. In the engine the pressure, temperature, and nozzles may be adjusted to help overcome any inhibited atomization caused by the additive. From a safety perspective, we would like the same chemical additive to prevent fuel from burning in the event of a leak or rupture under atmospheric conditions.

It is critical that the chemical additives used to control fuel flammability be stable and not promote fuel degradation.<sup>12-14</sup> Degradation is measured in terms of sediment formation that will ultimately plug nozzles and filters. Military fuels can be stored for as long as one to two years. Any low molecular weight acid compounds, alcohols, and aldehydes have reportedly been shown to promote jet fuel degradation.<sup>12-14</sup>

There are several types of atomizers that have been designed and utilized for various industrial and research applications.<sup>5-7,15</sup> A rotary atomizer has been selected for this application due to its inherent characteristics and versatility. For example, the droplet sizes of fuel can be easily controlled by the size and rotational speed of the atomizer. The instrument also enables the simulation of droplet linear velocities and shearing force effects on additives.<sup>16</sup>

The chemical complexity of jet fuel and other combustible liquids and the inherent characteristics of the rotary atomizer present several challenges to these studies. Thus we have begun studies with chemically simple systems to separate the properties of the aerosol from those

characteristics that are inherent to the experimental atomizer. In these studies the rotating body is a vaned disk and the systems are water and dilute aqueous solutions. From the results of these studies, correlation functions are emerging to predict aerosol distribution characteristics based on both aerosol properties and atomizer operating parameters.

## EXPERIMENTAL

All chemicals used in these experiments were of reagent grade. Ethylene glycol and glycerine were purchased from Fisher Scientific (Fair Lawn, NJ). The solketal was purchased from Acros Organics (NJ, USA). All deionized water used in these experiments was obtained on site. The four aerosol systems studied in the atomizer were water, 5% (v/v) glycerine solution, 5% (v/v) ethylene glycol solution, and 5% (v/v) solketal solution.

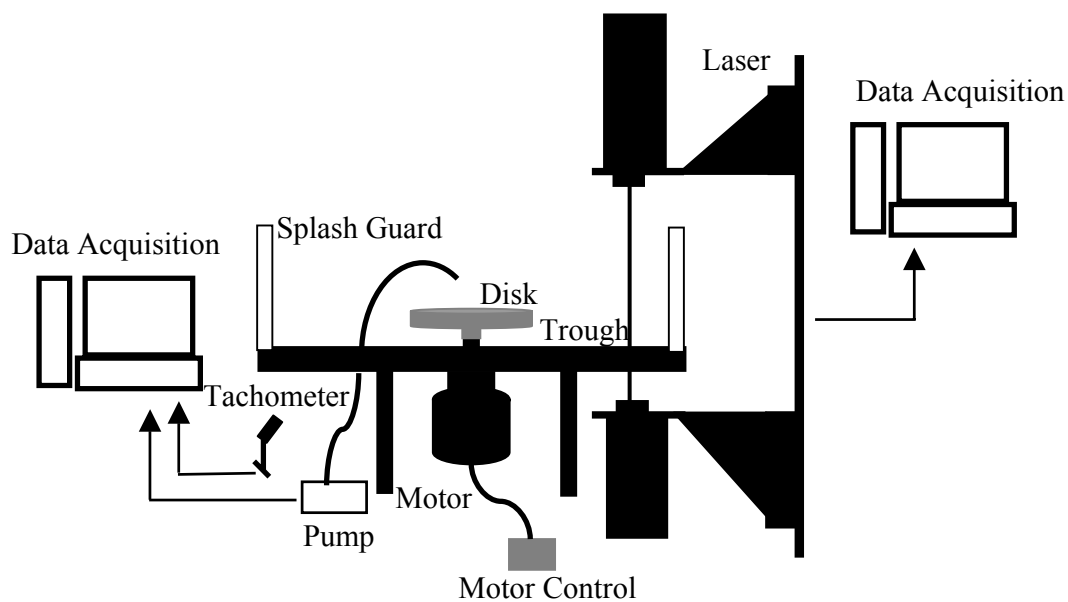


Figure 1. Schematic of Rotary atomizer apparatus

Figure 1 is a representation of the test apparatus. The aluminum test stand is comprised of a trough and splash guards to contain aerosol generation. At the center of the test stand is a rotating disk composed of aluminum that is 5.25 inches (13.22 cm) in diameter and 0.5 inches (1.27 cm) in thickness. The disk is driven by a 1 ¾ HP 1618 model Bosch router (120 V, 11 amps, 25,000 rpm) that is controlled by a router speed controller (Woodworker's Supply, Casper WY, model number 821-539). When the disk reaches a steady rotational speed, a peristaltic pump (Watson-Marlow, Model 323U/E, Energy Equipment Inc., Midlothian, VA) equipped with Tygon tubing (1/4" ID and 3/8" OD) (Saint Gobium Tygon Laboratory Tubing Formula R-3603 VWR Scientific Products) coupled to 1/8" OD stainless steel tubing delivers the fluid to the center of the disk cavity. The droplet size analyzer (Malvern Spraytec Malvern Instruments Inc., Southborough, MA), configured for continuous mode, takes size distribution measurements for 15 to 20 seconds. When the Spraytech measurements are finished for a set of experimental conditions, the flow to the disk is secured. Each aerosol system is studied over a range of rotational speeds (5400 – 9800 rpm) at a flow rate of 365 mL/min. The peristaltic pump, solenoid valve, and the ACT Series Panel/Bench Top tachometer (Monarch Instruments, Amherst, New Hampshire, model number 6140-051) are controlled by a LabVIEW data acquisition system (National Instruments, Austin, TX). The data acquisition system includes LabVIEW graphical program version 6 and a National Instruments SCXI-1001 Chassis populated with specific modules and terminal blocks (SCXI-1102, 1303 terminal block; SCXI-1124, 1325 terminal block; SCXI-1160, 1324 terminal block). A cross section of the disk and complete description of the test apparatus and its dimensions is available.<sup>17,18</sup>

## RESULTS AND DISCUSSION

The rotary atomizer relies on centrifugal forces to push the liquid through the radial holes. The mechanism by which the liquid breaks up into droplets is dependent on the intrinsic characteristics of the atomizer, its operating conditions, the liquid physical properties and feed rate.<sup>7-9</sup> To begin separating the apparatus characteristics from those of the aerosol, we began studying chemically straightforward systems. We primarily focused on adjusting atomizer disk speed and liquid surface tension.

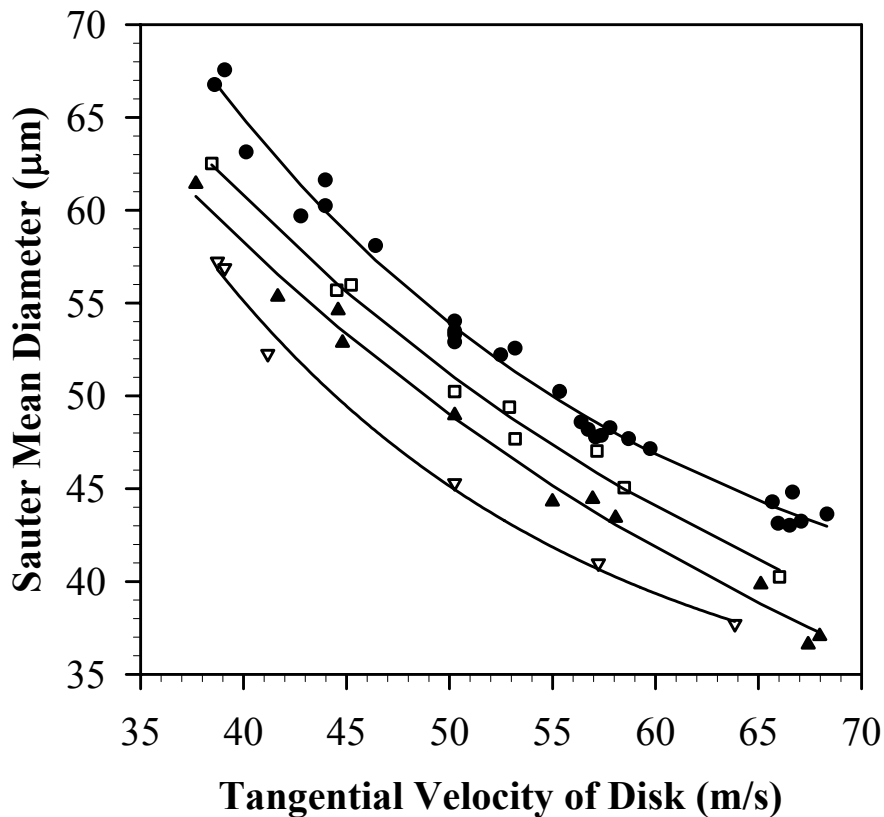


Figure 2. SMDs of aerosols [(●) water (73 dynes/cm), (□) 5% Glycerine system (72 dynes/cm), (▲) 5% Ethylene Glycol system (70 dynes/cm), (△) 5% Solketal system (59 dynes/cm)] as a function of rotary disk tangential velocity for a defined liquid surface tension and liquid flow rate to the center of the atomizer of 365 mL/min.

Figure 2 demonstrates how aerosol droplet size is affected by changes in the dynamic surface tension of water and disk tangential velocity. For a defined liquid feed rate of 365 mL/min to the center of the rotating body, the Sauter mean diameter (SMD) of the drops decreases as the disk tangential velocity is increased. As the surface tension of the water is decreased by the addition of additives (glycerine, ethylene glycol, solketal) the SMD decreases. The 5% (v/v) solketal solution produced the greatest change in SMD diameter which can be explained by the significant measured difference in dynamic surface tension. These results confirm that our apparatus behaves similarly to other rotary atomizers in its ability to generate a wide range of droplet sizes by simply adjusting the disk speed.<sup>7-9</sup> In terms of jet fuel flammability, these studies suggest that higher disk tangential velocities will translate into significant increases in fuel flammability. This is because the droplet evaporation rate is expected to follow an inverse  $d^2$ -law, therefore smaller droplets will enhance jet fuel flammability.

Figure 2 also high-lights the significant role surface tension forces have on droplet sizes. The ability to detect even small changes in surface tension affects, as shown in figure 2, will be a key factor in the development of chemical additives for fire safe fuels. For example, under room temperature atmospheric conditions, the surface tension of jet fuel (23 dynes/cm) is significantly less than the water systems presented in these studies. As the temperature of jet fuel is increased its surface tension is drastically reduced even further. Small changes in fuel surface tension by the addition of chemical additives, whose surface tension is greater than the jet fuel, could lead to dramatic increases in fuel droplet size. Increases in the fuel droplet size translate to a decrease in the fuel droplet evaporation rate and thus a reduction in fuel flammability.



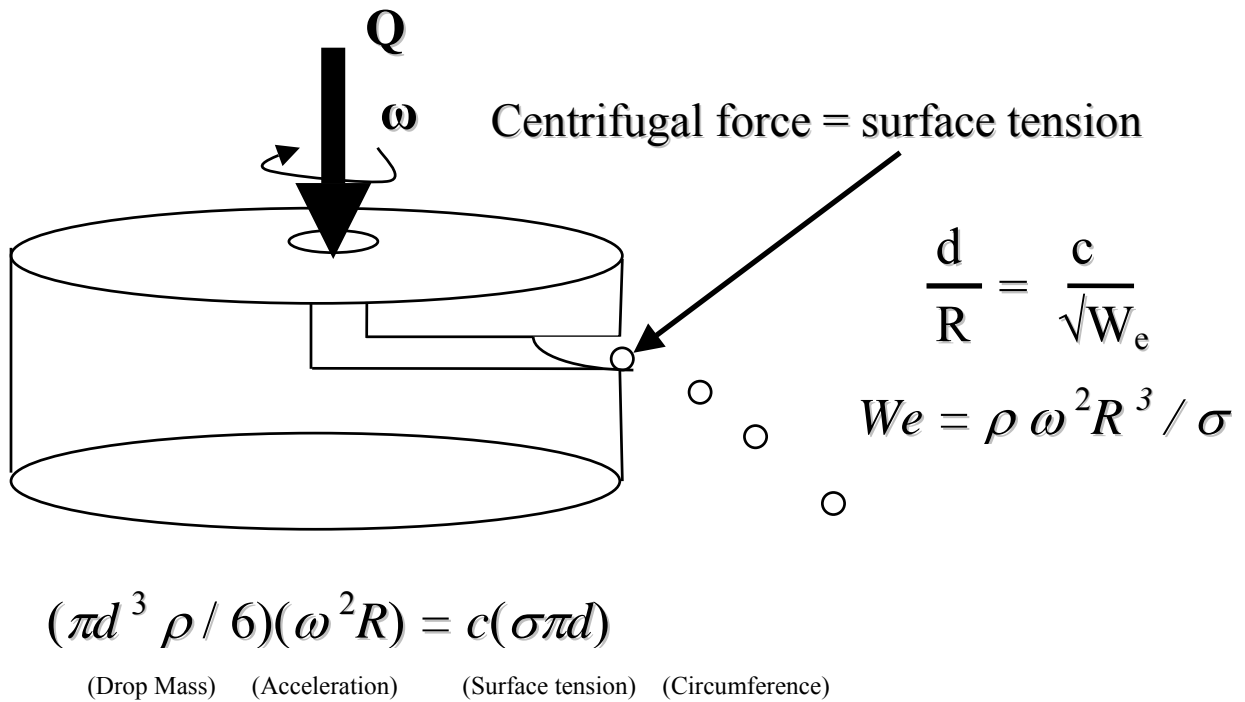


Figure 3. Schematic of Rotary atomizer's droplet mechanism

This phenomenon of liquid break up into droplets once it leaves a rotary disk has been described to occur by one of three mechanisms: atomization by direct drop formation, atomization by ligament formation, and atomization by film formation.<sup>7-10</sup> Direct drop formation takes place at lower flow rates around the edge of the disk. As the liquid feed rate is increased a sudden change to ligament formation occurs. Further increase in flow rate results in atomization by film formation. Figure 3 is a schematic of a possible mechanism of droplet formation at 365 mL/min liquid feed rate to the center of the rotating disk. The figure indicates that, under these defined operating conditions, atomization occurs when centrifugal forces of the disk equal the surface tension forces of the liquid as described below in equation 1.

$$(\pi d^3 \rho / 6)(\omega^2 R) = c(\sigma \pi d) \quad (1)$$

Here  $d$  is the droplet diameter,  $\rho$  is the density of the liquid,  $\omega$  is the rotational speed of the disk (rpm), and  $R$  is the disk radius. The equation may be rearranged in terms of the Weber number as shown in equation 2.

$$d/R = c(We)^{-1/2} \quad (2)$$

The Weber number is defined in equation 3.<sup>7</sup>

$$We = d^3 \rho \omega^2 / 8\sigma \quad (3)$$

Figure 4 illustrates the application of equation 2 to the droplet data obtained for our systems. This simple empirical relationship provides a good correlation between atomization behavior in our apparatus and the Weber number. The slight deviations in the relationship may be due to droplet transport issues that occur from droplet evaporation and coalescence. Such problems may be more evident when we transfer to fuel systems that have greater vapor pressure.

Figure 3 suggests the mechanism of atomization under these operating conditions is direct drop formation, however previous results indicate atomization occurs by ligament formation.<sup>18</sup> The direct drop mechanism describes these systems well because we are operating at fairly low flow rates and with relatively low viscous fluids. If the flow rate or viscosity is increased dramatically, we expect to see the growth of shear-induced instabilities on the jet opposed by surface tension forces. This will lead to differences in jet breakup length from the ligament.

Thus the droplet diameter will be dependent on both the Weber number and the Reynolds number. This will become critical to predicting atomization in our system when we begin studying more viscous liquids such as hydraulic fluids.

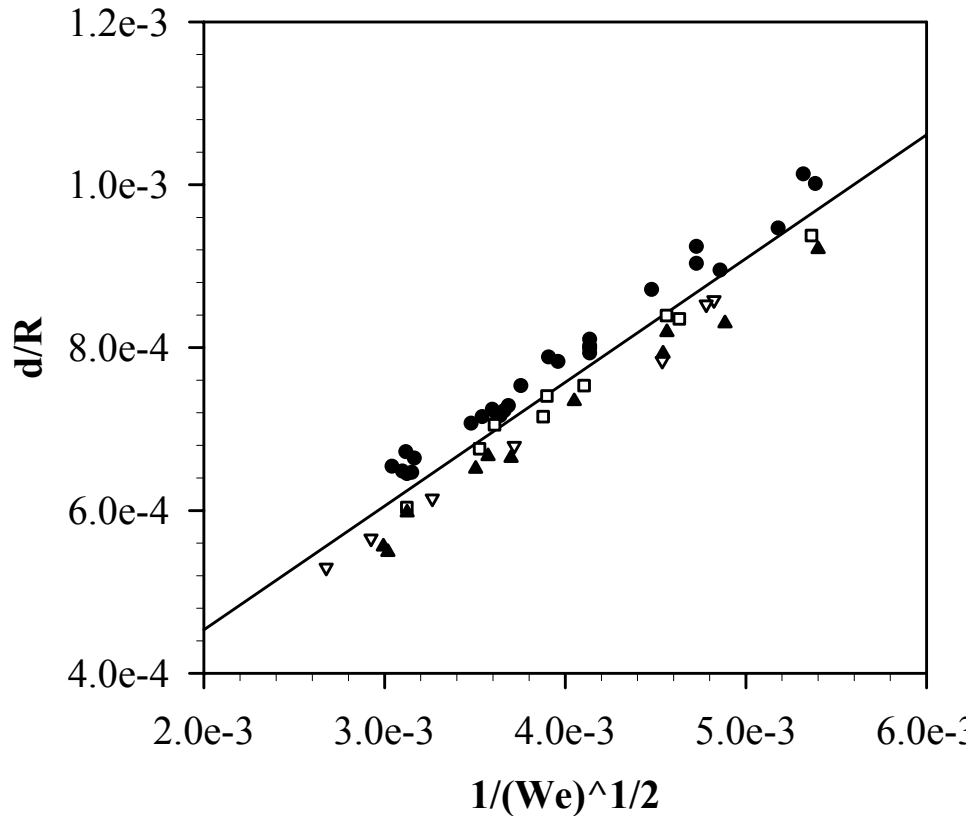


Figure 4. The ratio of the SMD to disk radius for water aerosols [(●) water (73 dynes/cm), (□) 5% Glycerine system (72 dynes/cm), (▲) 5% Ethylene Glycol system (70 dynes/cm), (△) 5% Solketal system (59 dynes/cm)] at a flow rates to the disk of 365 mL/min as a function of the Weber number.

## CONCLUSIONS

Water/additive aerosols generated with our apparatus behave in a reproducible and predictable fashion. The results also indicate the apparatus has similar characteristics as those found in the literature. However, fundamental aerosol and apparatus characterization will continue as we study systems differing significantly in physical and chemical properties such as

hydraulic fluids. This will further help to separate the properties of the aerosol for those characteristics that are inherent to the experimental apparatus. Thus we can continue developing a better more accurate empirical description of droplet formation. Preliminary experiments with actual fuels are underway. The results of these experiments will benefit both the military and civilian sectors by improving fuel safety for all middle distillate fuel applications.

## ACKNOWLEDGEMENTS

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