



MID-AMERICA TRANSPORTATION CENTER

Report # MATC-UI: 123

Final Report

UNIVERSITY OF
Nebraska
Lincoln

KSTATE
Kansas State University

KU
THE UNIVERSITY OF
KANSAS

MISSOURI
S&T
University of
Science & Technology


THE UNIVERSITY OF IOWA

 **LINCOLN**
University



Improving Freight Fire Safety: Analysis and Testing of Real Engine Conditions to Progress Development of Mist-Controlling Additives for Fire Mitigation

Albert Ratner, Ph.D.

Assistant Professor

Mechanical and Industrial Engineering

University of Iowa



THE UNIVERSITY OF IOWA

2010

A Cooperative Research Project sponsored by the
U.S. Department of Transportation Research and
Innovative Technology Administration

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the Department of Transportation University Transportation Centers Program, in the interest of information exchange.
The U.S. Government assumes no liability for the contents or use thereof.

MATC

**Improving Freight Fire Safety: Analysis and Testing of Real Engine Conditions to Progress
Development of Mist-Controlling Additives for Fire Mitigation**

Dr. Albert Ratner
Assistant Professor
Mechanical and Industrial Engineering
University of Iowa

A Report on Research Sponsored By

Mid-America Transportation Center
University of Nebraska-Lincoln

December 2009

1. Report No. 25-1121-0001-123	2.	3. Recipient's Accession No.	
4. Title and Subtitle Improving Freight Fire Safety: Analysis and Testing of Real Engine Conditions to Progress Development of Mist-Controlling Additives for Fire Mitigation		5. Report Date December 2009	
		6.	
7. Author(s) Albert Ratner		8. Performing Organization Report No. 25-1121-0001-123	
9. Performing Organization Name and Address		10. Project/Task/Work Unit No.	
		11. Contract © or Grant (G) No.	
12. Sponsoring Organization Name and Address Mid-America Transportation Center U.S. Department of Transportation Region VII University Transportation Center University of Nebraska-Lincoln 2200 Vine Street P.O. Box 830851 Lincoln, Nebraska 68583-0851		13. Type of Report and Period Covered	
		14. Sponsoring Agency Code MATC TRB RiP No. 24955	
15. Supplementary Notes			
16. Abstract (Limit: 200 words) The formation of a fuel mist resulting from high shear stresses acting on the fuel during violent sloshing and tank rupture under the energy of a crash severely increases the occurrence and intensity of fires in transportation related accidents. In order to minimize such crash-induced fires, adding long chained polymers to diesel fuel was proposed to arrest the break-up of diesel into a fine mist. Such polymers with specifically engineered properties are intended to impart non-Newtonian characteristics to diesel, which would then alter its flow behavior under the applied shear stresses. As a first step in this direction, calculations are performed to obtain the shear stresses experienced by diesel in a typical diesel engine fuel system. From this, a shear range was identified in which the added polymers should be most active and not affect the normal operation of the engine. In addition, drop impact experiments using high-speed imaging were carried out for diesel to characterize its flow behavior under a wide range of strain rates. Similar tests were performed with other common hydrocarbons to identify an appropriate simulant for diesel. Data generated from these tests enable validation for computer models of diesel drop impacts that are to be developed in the next phase of this project.			
17. Document Analysis/Descriptors		18. Availability Statement	
19. Security Class (this report)	20. Security Class (this page)	21. No. of Pages 15	22. Price

Table of Contents

List of Nomenclature	vi
Abstract	vii
Executive Summary	viii
Chapter 1 Introduction	1
Chapter 2 Analysis of Engine Fuel System	3
Chapter 3 Drop Impact Experiments	8
Chapter 4 Conclusions	15
References	16

List of Figures

Figure 2.1 Fuel system on a common-rail fuel-injection system: (1) fuel tank (2) pro-filter (3) pre-supply pump (4) fuel filter (5) low-pressure fuel lines (6) high-pressure pump (7) high-pressure fuel lines (8) fuel rail (9) nozzle (10) fuel return line (11) fuel-temperature sensor (12) ECU (13) sheathed- element glow plug.....	3
Figure 2.2 Standard Nozzle and Holder Assemble for Direct Ignition Engines.....	5
Figure 3.1 Spreading of a Liquid Drop on a Solid Surface at Atmospheric Pressure.....	9
Figure 3.2 The experimental arrangement: (a) actual set-up (b) schematic representation.....	11
Figure 3.3 Comparison of Maximum Spread Factors for Different Liquids.....	14

List of Tables

Table 2.1 Properties of Test Liquids at 20 °C.....	4
Table 2.2 Shear Stresses Distribution in a Representative Diesel Fuel System.....	6

List of Nomenclature

τ = Shear stress in liquid

τ_w = Shear stress at wall

\mathbf{u} = velocity field in the liquid

μ = viscosity of the liquid

V = Mean velocity of liquid flow

Q = Volumetric flow rate of liquid

d_p = Diameter of the pipe

ω = Angular velocity

r = Radius of blade

D_{eq} = Equivalent drop diameter

D_L = Larger diameter of the drop

D_S = Smaller diameter of the drop

d = Drop spread diameter at a given time

β = Spread factor

β_{max} = Maximum spread factor

t = Time after impact

Abstract

The formation of a fuel mist resulting from high shear stresses acting on the fuel during violent sloshing and tank rupture under the energy of a crash severely increases the occurrence and intensity of fires in transportation related accidents. In order to minimize such crash-induced fires, adding long chained polymers to diesel fuel was proposed to arrest the break-up of diesel into a fine mist. Such polymers with specifically engineered properties are intended to impart non-Newtonian characteristics to diesel, which would then alter its flow behavior under the applied shear stresses. As a first step in this direction, calculations are performed to obtain the shear stresses experienced by diesel in a typical diesel engine fuel system. From this, a shear range was identified in which the added polymers should be most active and not affect the normal operation of the engine. In addition, drop impact experiments using high-speed imaging were carried out for diesel to characterize its flow behavior under a wide range of strain rates. Similar tests were performed with other common hydrocarbons to identify an appropriate simulant for diesel. Data generated from these tests enable validation for computer models of diesel drop impacts that are to be developed in the next phase of this project.

Executive Summary

Most crash related fires in transportation occur due to the rapid ignition of a fuel mist that forms due to the intensity of the accident. Since it is known that pools of diesel burn relatively slowly, a possible way of mitigating such crash induced fires is to prevent misting by mixing long chained polymer based additives into diesel. Such polymers, still in the developmental stages, are intended to impart non-Newtonian viscosity (shear-thickening) to diesel in a shear range that is typical of accidents but is otherwise different from the shear stresses occurring during normal functioning of the fuel system. Such an increase of viscosity retards the break-up of a liquid into smaller droplets since the energy imparted to the liquid is dissipated due to its viscosity.

It is important to identify a range of shear stresses in which the polymer should have a maximum effect on fuel properties such that normal engine performance is not affected. For this purpose, a representative fuel system was studied to calculate the shear stresses occurring during the flow of fuel in different components. The analysis suggested that while the shear stresses in fuel lines and pumps are lower than 5000 Pa, shear stresses greater than 10^6 Pa occur in the injector, the area in which the fuel becomes atomized. A shear range of 10^4 - 10^5 Pa is most likely not to occur in the fuel system and hence has been identified as the target range in which the polymer should be most active.

Drop impact experiments were selected to study the flow behavior of diesel-polymer blends because such experiments can be performed with accuracy and repeatability and allow a continuous variation of shear stresses on the flowing liquid. A drop of liquid impacting a solid surface spreads within a very small time and causes the liquid to experience a wide range of strain rates. High speed imaging of the drop shape during spreading can provide useful insight into the effect of liquid properties on its flow behavior. Drops of diesel were tested at three different impact speeds so that flow of pure diesel can be understood and compared with that of polymer-diesel blends. Cetane, heptane, propanol and isobutanol were also tested at similar

speeds to identify the best dynamic simulant for diesel. Isobutanol was chosen as the simulant since it showed spreading behavior that most closely matched that seen for diesel.

The current study has shown that a shear range exists in which the properties of the fuel can be modified using a suitable polymer additive without affecting fuel flow in the components of the fuel system. Future work in this research would involve experiments with common polymers and the development of a numerical model of a drop impact process using Fluent. Current experimental data obtained from diesel drops will be used to validate the numerical model. Once an accurate model is ready, it would be possible to arrive at the desired properties of the polymer additive.

Chapter 1 Introduction

Despite advances in vehicle and passenger safety techniques—like crash-proof chassis design, robust fuel tanks, seat-belts, air bags and fire-extinguishers—transportation related accidents do occur and cause severe damages to life and property. Fire is a major cause of destruction in accidents because it erupts and engulfs the crash area. A crash-induced fire is greatly intensified due to the accelerated burning of a fuel mist that forms upon rupturing of the fuel tank. The resulting blaze can incinerate anything in the vicinity and hinder rescue operations. This mist burns so vigorously since it contains fine droplets of fuel suspended in the air which increase the surface area of burning and availability of oxygen. Conversely, pools of diesel are known to burn relatively slowly since the surface area exposed to oxygen is greatly diminished as compared to a mist. Hence, preventing the formation of a fuel mist can help in minimizing the intensity of crash-induced fires. An effective way of achieving this goal is to develop suitable fuel additives to alter the flow properties of diesel, thus retarding its disintegration into fine droplets under the conditions typical to an accident. Advances in chemistry of long-chained polymers might enable the development specific additives to suit the purpose.

The above idea utilizes the fact that the addition of long-chained polymers to a solvent imparts non-Newtonian flow characteristics. The resulting blend exhibits a shear-dependent viscosity; that is, the faster the liquid flows, the thicker (or thinner) it becomes. During an accident, as the fuel sloshes violently and flows out of the tank, it experiences high strain rates—hence shear stresses. A suitable polymer additive that increases the fuel viscosity in this range of strain rates would retard fuel disintegration into fine droplets, thereby preventing mist formation. This is because much higher energy is required to cause the atomization of a high viscosity liquid. However, it is important that such changes in fuel properties do not affect the normal functioning of the fuel system and the engine. Therefore, diesel flow in a representative fuel system has been studied to calculate approximate values of shear stresses that the fuel

experiences in different components. A target shear stress range has been identified that avoids the values occurring in the fuel system and at the same time matches the values that might occur in vehicular accidents.

To test the effect of polymer additives, a suitable experiment must be devised that enables us to observe the effect of change of liquid viscosities. High speed imaging of an impacting liquid drop provides a simple tool in which the liquid is subjected to a wide range of strain rates from as high as 10^6s^{-1} to nearly zero. Spreading and splashing of drops are inherently related to liquid properties, like surface tension and viscosity. The effect of the variations in viscosity occurring due to continuously changing strain rates during a drop impact can be studied by observing the shape of the spreading drop and its spread diameter. As a first phase of experiments, tests were carried out with diesel to characterize its flow behavior in a deforming drop. This data would enable the identification of differences caused in flow due to addition of polymers. Cetane, propanol, heptane and iso-butanol were also tested to establish a simulant for diesel.

The second phase of this research would focus on testing the effect of some common large molecular weight polymers on the flow properties of diesel. In addition, a computational model of a drop impact process will be developed using commercial CFD software Fluent which will be then used to study the effects of varying liquid properties without having to actually perform the tests. The results of the experiments will be used to validate the CFD model so that accuracy of predictions can be ensured. The experiments and computational analysis can then be used to provide feedback for developing polymers with the required properties. This report presents the work carried out in the first phase of the research, which includes analysis of a representative engine system and initial drop impact tests.

Chapter 2 Analysis of Engine Fuel System

A fuel supply system in a diesel engine commonly consists of several components, like a fuel tank, low pressure pump, low pressure fuel pipeline, a high pressure pump, a high pressure fuel pipeline and an injector, as shown in figure 2.1. The low pressure pump collects fuel from the fuel tank and supplies it to the high pressure pump through the low pressure line. The high pressure pump supplies fuel to the injector at a very high pressure which then sprays the fuel in the engine cylinder. While flowing in the circuit, diesel experiences shear stresses that vary in magnitude at different locations depending mainly on the flow velocities.

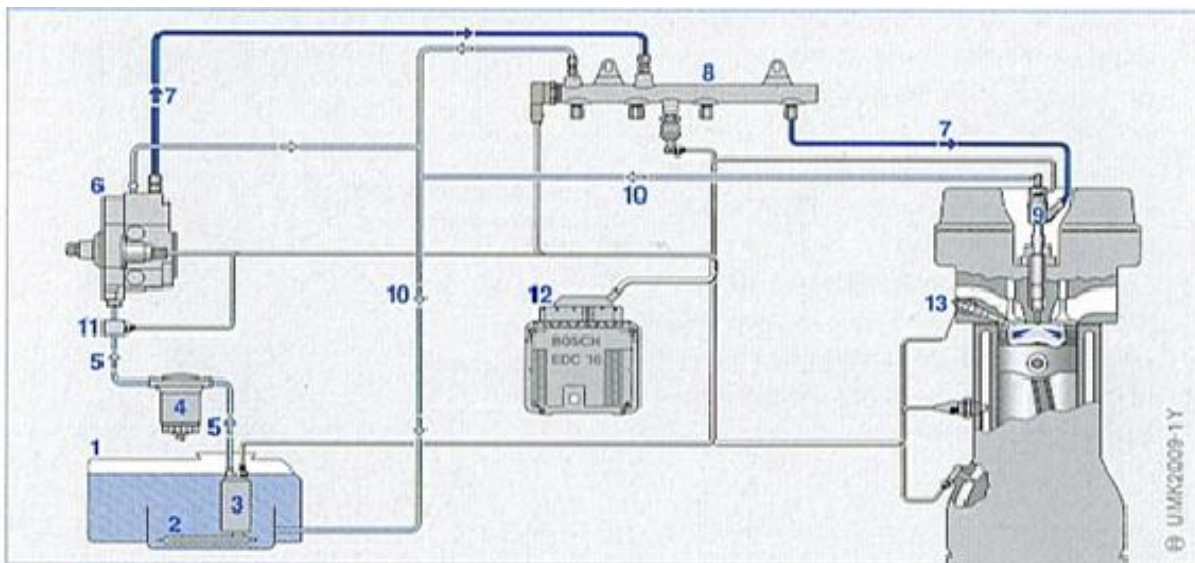


Fig. 2.1 Fuel system on a common-rail fuel-injection system: (1) fuel tank (2) pre-filter (3) pre-supply pump (4) fuel filter (5) low-pressure fuel lines (6) high-pressure pump (7) high-pressure fuel lines (8) fuel rail (9) nozzle (10) fuel return line (11) fuel-temperature sensor (12) ECU (13) sheathed- element glow plug

As mentioned earlier, it is of utmost importance to identify a target range of shear stress in which the polymer should be active so that it does not affect the performance of individual components. For example, the polymer must not increase the fuel viscosity at lower shear rates that typically occur in the pumps and the fuel lines because that would lead to increased pumping losses. Neither should the polymer become activated at the extremely high shear rates that

typically are found in the injectors as it might affect the quality of atomization, which in turn would affect engine combustion. Hence, flow analysis for a representative fuel system was carried out to estimate the shear stresses occurring in different parts of the fuel system under a nominal operating condition. It must be mentioned that fuel flow rates, and hence the shear stresses, vary with the operating conditions (load and power) of the engine.

Table 2.1 Properties of Test Liquids at 20 °C

Liquid	Density (kg/m³)	Viscosity (mPa-s)	Surface tension (mN/m)
Diesel	~830	3.61	~28.0
Cetane	773	3.507	28.12
n-propanol	803.4	1.97 (25°C)	23.70 (25°C)
Heptane	684	0.386 (25°C)	20.14
Isobutanol	805	3.77 (25°C)	24.0

Since diesel is a complex mixture of a large number of hydrocarbons, its properties vary from source to source. Depending on its properties, diesel is available in three commercial grades: Diesel No. 1, Diesel No. 2 and Diesel No. 4. Diesel No. 1, also known as truck diesel, is used in most road and rail transport applications. Used in vehicle engines, several additives are added to this type of diesel to improve properties like anti-freezing, deposit formation, and so forth. Hence, significant variations may be observed in properties between different diesel samples. For flow calculations, reference values of transport properties were assumed, as listed in table 2.1. A brief description of calculation for shear stresses is presented as follows.

Shear stress in a flow is given as:

$$\tau = \mu \frac{du}{dy} \quad (2.1)$$

For a one-dimensional flow such as those encountered during flow in thin pipes, the above expression becomes

$$\tau_w = \mu \left(\frac{dv}{dy} \right)_{y=R} \quad (2.2)$$

For flow in pipelines, maximum shear stress is observed at the walls of the pipe because of the high velocity gradients at the walls. The mean velocity of flow is given as:

$$V_m = \frac{1}{A} \int_0^R v(r) 2\pi r dr \quad (2.3)$$

The Reynolds' number (Re) of flow can be calculated using this velocity. For laminar flows ($Re \leq 2300$) the shear stress on pipe walls is given by:

$$\tau_w = \frac{4\mu V_m}{R} \quad (2.4)$$

For turbulent flows ($Re > 2300$) wall shear stress is given as:

$$\tau_w = \frac{f \rho V_m^2}{2} \quad (2.5)$$

where f is the friction factor obtained from the Moody chart. Typically, to calculate shear stress in the injector two separate parts are considered: the pipe in the injector and the nozzle (see fig. 2.2).

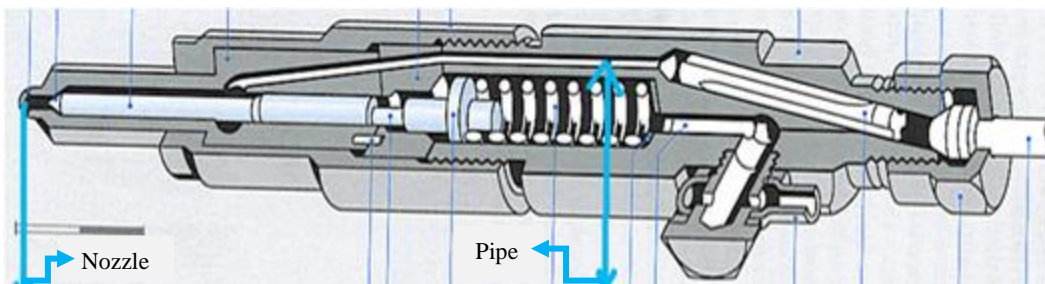


Fig. 2.2 Standard Nozzle and Holder Assemble for Direct Ignition Engines

Both of these parts are treated as pipes; thereby, the above equations are also suitable for the injector. The fuel is subjected to shear stresses in the pumps due to centrifugal action of the vanes or the blades. The highest shear stresses occur at the tip of the blades where the velocities are highest and given as

$$\tau_w = \rho v^2 r \quad (2.6)$$

Hence the shear stress in the pump can be given as:

(2.7)

For a typical flow rate, $Q = 1.4435 \times 10^{-5} \text{ m}^3/\text{s}$, shear stresses calculated in different parts of the fuel system using the above expressions are listed in table 2.2. It can be seen that the lowest shear stress (0.4 Pa) occurs in the low pressure pump, while the highest ($3.87 \times 10^6 \text{ Pa}$) occurs in the injector. It is evident that there is a wide enough range of shear stresses between $10^4 - 10^5 \text{ Pa}$ which is significantly different from those occurring in the fuel system components. Sloshing of fuel under conditions of an accident could also induce a wide range of shear stresses. Though the shear stresses are not as high as in the injector, values in the range of $10^4 - 10^5 \text{ Pa}$ can cause the breaking-up of diesel into smaller droplets. Hence, if a polymer is designed that has maximum effect in the range target range of $10^4 - 10^5 \text{ Pa}$, formation of very small droplets occurring during a tank rupture can be avoided. Change in properties caused due to the polymer would have a minimal effect on the performance of the fuel system since the range of shear stresses targeted is disparate from the working level of shear stresses in different parts of the fuel system.

Table 2.2 Shear Stresses Distribution in a Representative Diesel Fuel System

Label as in Fig.	Component	Velocity	Shear Stress (Pa)
A	low-pressure pump	1000 rpm	0.4
B	pipe (low)	0.204 m/s	0.653
C	high-pressure pump	3000 rpm	1.19
D	pipe (high)	2.04 m/s	20.67
E	pipe in the injector	28.7 m/s	2871
F	nozzle	1275.9 m/s	3.87 E6

Thus, an analysis of a common diesel fuel system was carried out to identify a range of shear stresses in which the polymer additive should be most active. The next step is to carry out

tests in order to understand the flow behavior of diesel. A simple experiment for this purpose is described in the next section.

Chapter 3 Drop Impact Experiments

Since the polymer additive is expected to impart non-Newtonian viscosity to diesel, a simple experiment allowing an easy variation of shear stress applied to the fluid is needed to study the flow behavior of polymer-diesel blends. The experiment should also permit a study of the desired parameters with accuracy and repeatability. High speed imaging of the liquid drops impacting on a dry smooth surface provides an effective way of achieving the above goals. A liquid drop deforming upon impact on a solid surface experiences a wide range of strain rates. For example, a drop of 1 mm diameter impacting at a speed of 1 m/s can experience strain rates as high as 10^6s^{-1} in the initial stage of deformation while strain rates are close to zero near the maximum diameter of spread.

During the impact of a liquid drop on a solid surface, the drop can either spread from its initial spherical shape to a thin disk like shape, or splash into droplets. The outcome is dependent on a number of factors such as viscosity, surface tension and density of the liquid, drop speed and size, nature of the impact surface, its surface roughness and temperature, and the surrounding gas. A sequence of a drop spreading on a solid surface is shown in figure 3.1. In the initial stage of a drop impact, a thin layer of liquid called lamella moves radially at speeds that can be several times higher than the impact speed. Extremely large strain rates, or stretching, occur in the lamella since its spreading speed is high and its thickness is small—it is up to one-hundredth of the drop diameter. Surface tension and viscosity of the liquid quickly decelerate the lamella and cause its thickening. With time, the diameter of this lamella attains a maximum after which, depending on the nature of the liquid, it can spread further as a very thin film at much slower speeds, recoil, or become static. This entire process of spreading up to the maximum diameter occurs in a few milliseconds. Accordingly, high speed photography becomes important in studying such impact processes. The ratio of the diameter of the spreading liquid at any time instant after impact to the initial drop diameter is called the spread factor β . At the maximum spread diameter, this ratio is called the maximum spread factor β_{max} . Since spreading of a drop is

inherently tied to its properties, variations of maximum spread factor can be used as a parameter for comparison between the properties of different liquids. Rate of spreading is another quantity that can yield useful insights into the effect of changes in the liquid properties. For example, for impacts with similar drop speed and size a high viscosity liquid is expected to show lower spreading velocities. The present experiments have investigated these quantities for pure diesel and some common hydrocarbons.

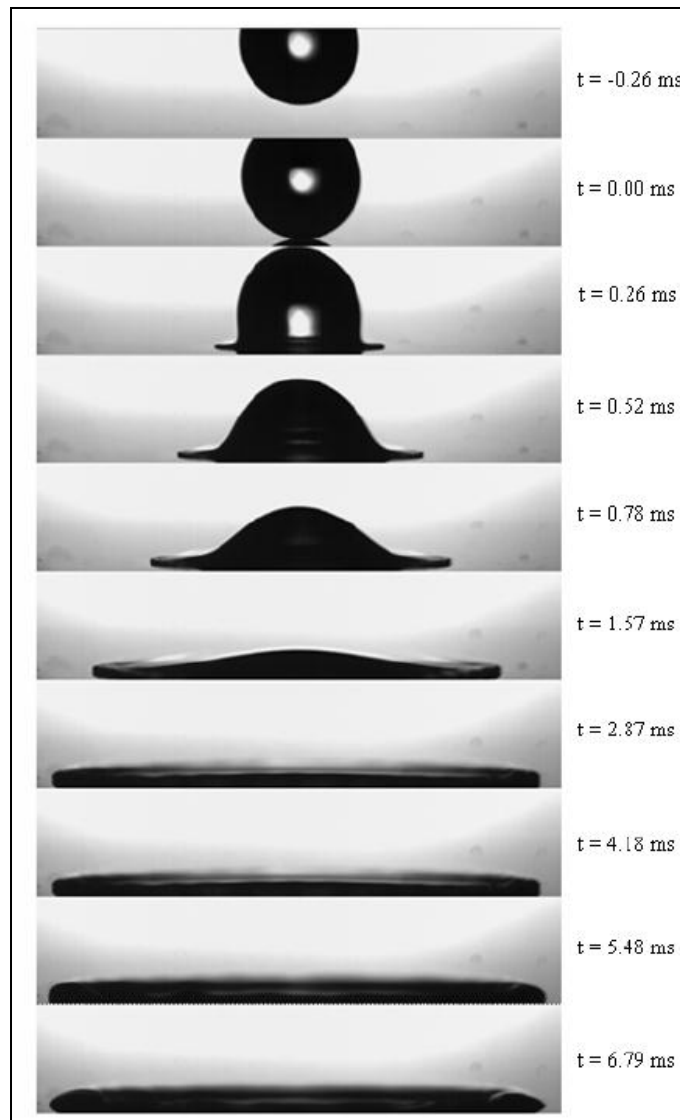
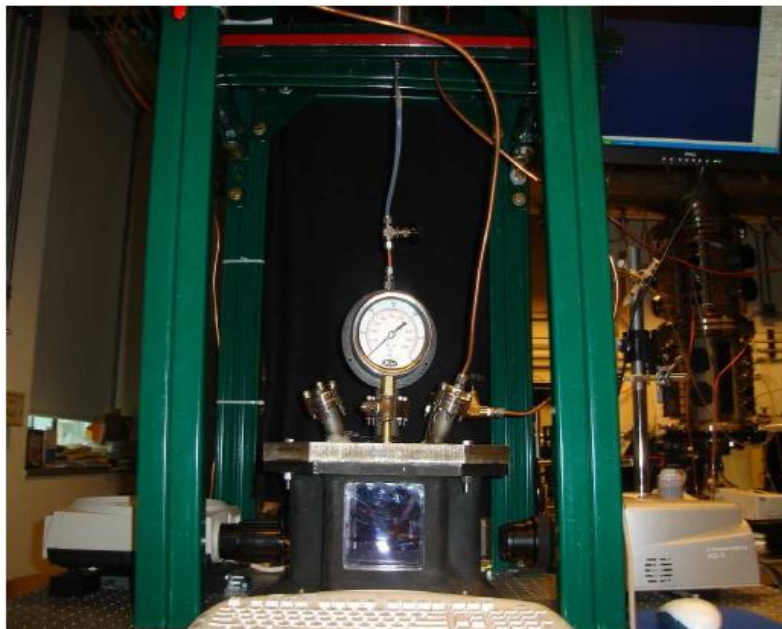


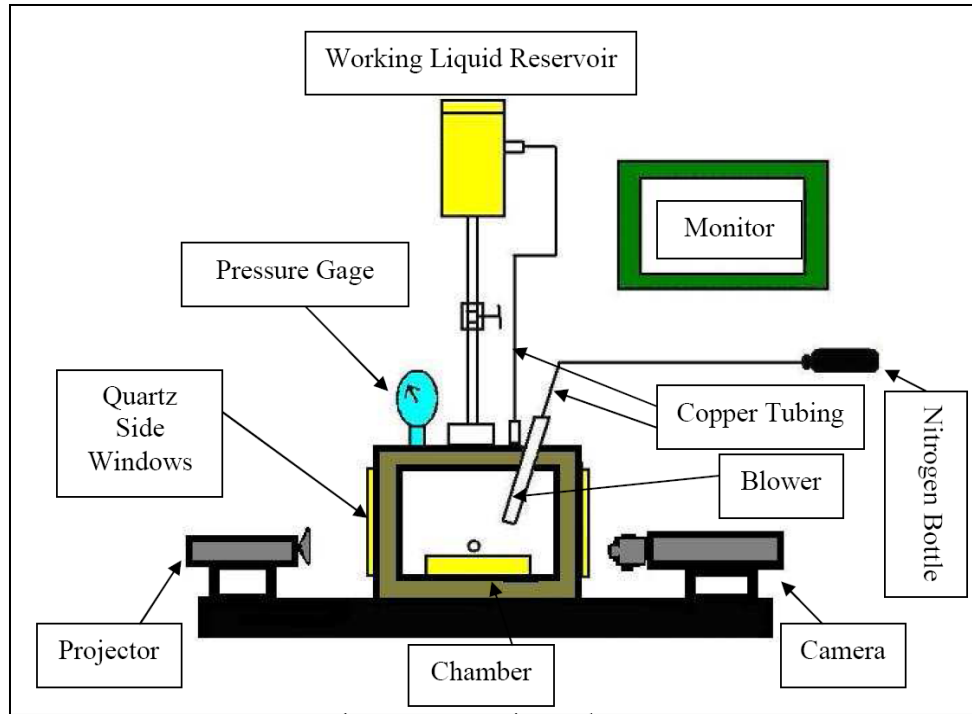
Fig. 3.1 Spreading of a Liquid Drop on a Solid Surface at Atmospheric Pressure

3.1 Experimental Arrangement and Procedure

A schematic of the experimental arrangement is shown in figure 3.2. The arrangement mainly consisted of a pressure chamber with a 6" x 6" x 6" working volume for testing. It was constructed by welding together four steel C-sections forming the side-walls which were then welded onto a thick steel base. A flange was welded on the top portion of the walls to enable bolting of a lid for sealing the chamber. An adaptor could be mounted on top of the lid to hold the drop generator. The C-sections had 6" x 6" cutouts where four 44 mm thick transparent windows were affixed for viewing the impacting drop. Inside the chamber a 5" diameter cylindrical quartz block was fixed as the impact surface. The block was made of highly refined NSG "N" quartz material smoothed to $1/4\lambda$ ($\lambda = 619$ nm) across a 5.08 cm diameter area. Such a high degree of flatness and surface finish ensured that only the effects of pressure on drop impacts could be isolated, while the effect of surface roughness, inclination, and other elements was eliminated. The chamber could be pressurized to the desired level using nitrogen gas supplied from compressed gas cylinders. However, the present tests have been carried out at atmospheric pressure with the chamber lid kept open.



(a)



(b)

Fig. 3.2 The experimental arrangement: (a) actual set-up (b) schematic representation

A blunt-end hypodermic needle enclosed in transparent PVC tubing was used as the drop generator. For open-chamber tests the tube-needle assembly was held in position over the impact surface using fork clamps. Test liquid was supplied to the needle from an overhead reservoir through a PVC pipe with a ball valve and a needle valve in between to regulate flow through the needle. All tubing connections were made using steel fasteners from Swagelok. The height of the fork clamp could be varied to change the impact speed of drops. The impacting drops were videographed approximately normal to the direction of incidence using an IDT XStream-Vision XS-3 digital camera with a Nikon 105mm f/2.8D Micro-Nikkor lens. A 300 W projector lamp was used to create a bright background against which sharp images of the falling drops could be visible. A millimeter scale was used to obtain the calibration factors for conversion from pixels to millimeters.

Drop impact tests were performed at three impact speeds for diesel and pure hydrocarbons—namely, for cetane, n-propanol, heptane and iso-butanol. These hydrocarbons are commonly used as simulants in various fuel-related experiments. A step-by-step description of the experimental procedure is given below.

1. Setting the needle valve and needle height

The overhead reservoir was filled with test liquid that was allowed to run through the needle to eliminate any trapped bubbles in the liquid line. The needle valve was set to a fixed small opening for slow drop release in correspondence with opening or closing of the ball valve.

2. Setting and focusing the camera

The camera was set to capture images with sufficient background brightness and field of view, to ensure that the full drop was visible in at least one of the frames. Several trial drops were allowed to fall, and were recorded by suitably adjusting the camera focus to obtain images of desired sharpness and clarity. Using these images, the height of the needle was adjusted to obtain a particular impact speed.

3. Cleaning the impact surface

Once the settings were ready for actual tests, the impact surface was cleaned using xylene and acetone, and was wiped dry using lintless lens cleaning tissues.

4. Imaging and recording drops

For collecting actual data, the camera was set to record around 4000 frames per second with a total recording time of nearly 1 second. A single drop was allowed to fall from the needle slowly under the effect of gravity. Just before the drop was released, the camera was manually triggered to capture the entire impact process. Fifty to sixty frames spanning the period of interest, depending on the test objective, were saved.

5. Repeat steps 3 and 4

Steps 3 and 4 were repeated to obtain 10 to 15 drops at a given impact speed to average out the minor variations. Only in-focus and nearly spherical drops were saved.

6. Calibration and calibration factor

Once a set of drops was recorded for a particular condition, a standard millimeter scale was photographed in the same focal plane as the drops. A calibration factor (mm/pixel) was obtained by dividing the distance (in mm) between two extreme graduations visible in the image of the scale by the camera pixels separating them as read off the screen.

Drop diameters were read off the screen by measuring pixel distance between two diametrically opposite points. It was observed that the drops were not perfectly spherical and, as such, diameters were measured along both the horizontal and the vertical axes. Assuming symmetry in the azimuthal direction, the drop was considered as an ellipsoid for which an equivalent diameter D_{eq} was calculated as $(\dots)^{1/3}$. This diameter in pixels was converted to millimeters by multiplying with the calibration factor. Drop distortion, measured as the difference of D_L and D_S , was within 1% of the equivalent drop diameter D_{eq} .

Impact speed was obtained by dividing the distance travelled by a drop in the last two frames prior to impact by the time interval between the two frames. Spread factors for a deforming drop could be calculated at each time interval by dividing the spread diameter at that instant by D_{eq} . Spreading velocities for a given drop impact were calculated at each time instant by dividing half the change of spread diameter between two successive frames, with the time interval between the two frames. That is:

$$\underline{\hspace{2cm}} \tag{3.1}$$

where, k denotes the current frame, V_k denotes the spreading velocity at the time instant corresponding to frame k , d_k is the spread diameter in the current frame, d_{k+1} is the spread diameter in the next frame and Δt is the time interval between successive frames depending on the frame speed used.

3.2 Results

As stated earlier, drop impact tests were performed for diesel, cetane, propanol, heptane and isobutanol. A 23 gauge needle was used to obtain drop sizes in the range of 2.00 – 2.10 mm, with drop size being affected by liquid properties. All the liquids were tested for three different impact speeds—1.6 m/s, 1.2 m/s and 0.7 m/s. A plot of the maximum spread factor θ_{max} with impact speed is shown in figure 3.3.

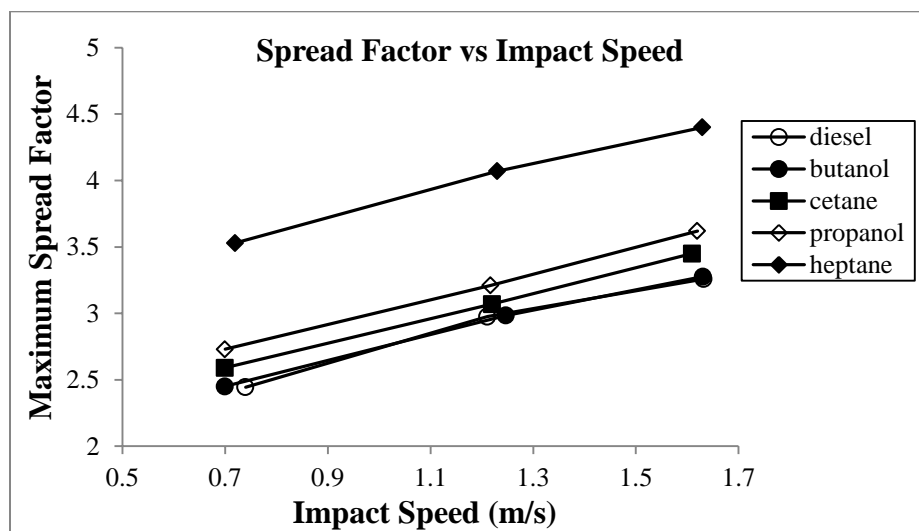


Fig. 3.3 Comparison of Maximum Spread Factors for Different Liquids

It can be seen that heptane has the highest value of θ_{max} . This is because the viscosity of heptane is the lowest among the liquids tested. Lower viscosity means lower energy dissipation during spreading and hence a high spread factor. Spread factor for diesel is the lowest owing to its relatively high viscosity. Though the viscosity of isobutanol is similar as that of diesel, it shows a slightly higher spread factor than diesel. This is a behavior that can be attributed to its lower surface tension. Cetane and n-propanol show greater spread factors than diesel because of their comparatively lower viscosities. Hence, based on this comparison of spread factors, it is apparent that isobutanol resembles the flow behavior of diesel most closely. Thus, iso-butanol was selected as a simulant for diesel and was used to conducting drop impact tests with polymer additives.

Chapter 4 Conclusions

An analysis of a typical diesel fuel system was performed to estimate the flow conditions and approximate shear stresses in different components of the fuel system. It was observed that, as expected, highest shear stresses ($> 10^6$ Pa) occur in the injector where the fuel is atomized into a very fine mist. Stresses in the pipelines and pumps are comparatively much lower (< 5000 Pa) such that, even if the variation in shear stresses due to varying operating conditions is accounted, a wide range of shear stresses between $10^4 - 10^5$ Pa exists. This conclusion is appropriate, considering the operating conditions of the fuel systems. Fortunately, this shear range is also typical of accident conditions under which fuel misting occurs. Hence, if a polymer additive could be engineered such that it imparts higher viscosity to diesel in this shear range, disintegration of diesel into fine droplets can be avoided without affecting the performance of the fuel system.

In order to test the effect of the addition of polymers on the flow behavior of diesel, high speed imaging of impact of liquid drops on a smooth surface was selected as the experimental tool. Drop impacts were obtained for diesel, cetane, propanol, heptanes and isobutanol at three different impact speeds. It was found that the maximum spread factors of isobutanol were similar to those of diesel. Hence, isobutanol has been selected as the simulant for diesel for future tests with polymers.

The second phase of this research will focus on performing initial experiments with polymer-diesel blends using some common polymers. A numerical model of a drop impact process will be developed using commercial CFD code Fluent. The results of the experiments and the numerical analysis can then be used to arrive at the appropriate values of properties of the polymer.

References

1. Rafai, S., D. Bonn, and A. Boudaoud. "Spreading of non-Newtonian fluids on hydrophilic surfaces." *Journal of Fluid Mechanics* 513 (2004): 77-85.
2. Betelu, S.I. and M.A. Fontelos. "Capillarity Driven Spreading of Power-Law Fluids." *Applied Mathematics Letters* 16 (2003): 1315-1320.
3. Rozhkov, A., B. Prunet-Foch, and M. Vignes-Adler. "Impact of drops of polymer solutions on small targets." *American Institute of Physics, Physics of Fluids* 15.7 (2003).
4. Rozhkov, A., B. Prunet-Foch, and M. Vignes-Adler. "Dynamics and disintegration of drops of polymeric liquids." *Journal of non-Newtonian Fluid Mechanics* 134 (2006): 44-55.
5. Tanner, L.H. "The spreading of silicone oil drops on horizontal surfaces." *Journal of Physics : Applied Physics* 12 (1979).
6. Guillou, S. and R. Makhloufi. "Effect of a shear-thickening rheological behavior on the friction coefficient in a plane channel flow: A study by Direct Numerical Solution." *Journal of non-Newtonian Fluid Mechanics* 144 (2007): 73-86.
7. Cheny, J.M. and K. Walters. "Rheological influences on the splashing experiment." *Journal of Fluid Mechanics* 86 (1999): 185-210.
8. Pascal, H. "Similarity solutions to some unsteady flows of non-Newtonian Fluids of Power Law Behavior." *International Journal of Non-Linear Mechanics* 27.5 (1992): 759-771.
9. Riazi, M.R. "Characterization and properties of petroleum fractions." 1st ed. ASTM.
10. "Diesel Fuel Exhaust and Emissions: Environmental Health Criteria 171." A draft report of United Nations Environment Program.