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# Matching refractive indices of two fluids and finding interfacial tension for the purpose of fuel spray imaging

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**Abstract.** This study attempts to prepare a fluid pair for use in spray dynamics investigations. Better understanding the behavior of fuel sprays is one of the things that can help improve the efficiency of internal combustion engines. To address the scattering issue in current imaging methods, the refractive index difference between the injected fluid and the medium that it is injected into is eliminated. Two immiscible fluids (sucrose solution and silicone oil) with the same refractive index was identified, their surface tension to build a model fluid engine system injection was also studied. At the same time, Weber number is found to help correct the difference. Results show that 63.7% mass sucrose solution has the same refractive index as silicone oil, and the sucrose solution/silicone oil interface has a surface tension of 0.08941 N/m, which is roughly four times larger than that of ethanol/air. This means using the sucrose/silicone oil fluid pair to model fuel spray will involve some adjustments to be accurate.

## 1. Introduction

It is completely necessary to effort towards more efficient vehicles. Even though the automotive industry is beginning to make the transition to electric and other alternative drivetrains, internal combustion engines are expected to play an important role in transportation and other fields until at least the next century. Fuel injection is a necessary function of most conventional internal combustion engines today. The spray of a fuel injector is an important subject to study because when it is better understood, it can be taken advantage of to create more optimal combustion. A detailed model of near nozzle sprays would serve to improve different aspects of the engine. Unfortunately, not enough is known about how fuel sprays behave to predict them from first principles [1-2]. If a simple, easily accessible visualization technique exists, much more experimental data can be gathered to help build accurate models of sprays. The main problem this study attempts to address is imaging the near nozzle spray of fuel injectors in a cost efficient manner [3-4]. Currently, there is a lack of understanding of the fundamentals of fuel injection. Imaging of fluid sprays have been attempted before. Argonne National Laboratory has the necessary X-ray equipment to reveal the structure of a fluid spray, but it is the only facility in the world that has such capability. Since 2005, it has been conducting a study to better understand fuel injection and sprays, and to develop improved spray models with annual budgets of about $1 million. A less costly way to study fuel sprays would benefit the industry in that it would make spray analysis more widely accessible, speeding up the development of more optimized engines. A very recent investigation into fuel spray imaging [5] makes use of a high speed camera with a framerate of 1,000,000 fps. Fuel is injected through a light source and the effects of fuel type and varying injection pressure on spray propagation is analyzed. It was discovered that injection pressure does not significantly affect the atomized region of a spray, and

there is a close correlation between viscosity and "mushroom length", the end region of a spray that resembles a mushroom [6]. The images created showed the space occupied by the spray in its entirety as a black shaded area, not revealing the structure of the spray or its breakup process. This is caused by the high optical density of the spray. The particle cloud in the spray is so dense that when light travels through it, scattering caused by refraction through each individual particle makes it impossible to clearly visualize the structure of the spray through this technique. If the phenomenon of refraction did not exist, this technique would produce images that showed a liquid core, which would be a small black shaded area in the middle; and a cloud of distinct fuel particles surrounding the core.
The study outlined by this article attempts to solve the scattering problem with this idea. Scattering is caused by a difference in index of refraction. By injecting a fluid into a medium of the same refractive index, scattering is eliminated. This study consists of identifying two immiscible fluids with the same refractive index, and finding their surface tension. Weber number can be calculated once surface tension is known, and that can be used to correct differences between our fluid pair and a real air/fuel spray.

## 2. Materials and method

### *2.1. Selecting fluid pair*

The pair of fluids for this investigation was chosen based on two main criteria: immiscibility and matched (or the ability to match) refractive index. Cost and safety of handling would also be factors that would affect the final decision. All possible pairs are listed in Table 1. Glycerin (n=1.466) is immiscible with both amyl acetate (n=1.4017) and acetone (n=1.3588), benzene (n=1.5014) would have to be added to them to bring their refractive index up to that of glycerin; cyclohexane (n=1.4262) is immiscible with both ethanol (n=1.36) and methyl salicylate (n=1.523) mix, the mix can be mixed in varying ratios to achieve any refractive index between their own; 200 mPa.s silicone oil and sodium iodide solution pair is immiscible, the refractive index of a sodium iodide solution can be modeled as a linear function of its concentration, both of the two fluids are non-toxic, but iodide is costly. In the study, sucrose solution can also be considered instead of sodium iodide [7], as it is also immiscible with silicone oil and it can reach a maximum refractive index of 1.5 which is above the index of silicone oil. The major benefit of using sucrose solution is that it is very cost effective, so the silicone oil/sucrose solution pair proves most appropriate for the following investigation.

**Table 1.** Possible fluid pairs that have been considered.

| Fluid pair (fixed fluid/adjustable concentration fluid) | Silicone oil /sodium iodide solution | Glycerin/amyl acetate or acetone | Cyclohexane/ethanol and methyl salicylate mix with Benzene added | Silicone oil/sucrose solution |
|---|---|---|---|---|
| Target Index (n) | 1.453 | 1.466 | 1.4262 | 1.453 |

### *2.2. Index matching*

The apparatus (Figure 1) made by our lab includes a container with four transparent windows and a frame to hold a motor for stirring the fluid mix. Fused silica was used as the viewing windows on the container, due to having the same refractive index (1.4585) as our target. There is an impeller driven by a motor reaching into the container for creating disturbances within the two fluids. A laser could shine through the fluid mixture via the windows, which could be index matched. The motors are mounted on an 80/20 extrusion frame, with mounting brackets that allow the motor positions, and in turn, positions of impellers within the container, to be adjusted. The mounting brackets each have a single straight slot for accurate and easily quantified adjustment of motor position. The "blender method" created by our lab is used to check whether two fluids have the same index as light scatters when it travels from one medium to another with a different refractive index.

Both fluids from a pair are poured into the apparatus with the adjustable index fluid at a high concentration (67.9%). The impeller was turned on while being careful not to exceed a speed that induces cavitation or pulls pockets of air into the mixture. If this happens, there will be unwanted refraction as the laser travels through these gaseous phases. The laser was turned on and positioned to travel right through the container windows, not hitting the impeller shaft or any remnants of sealant at the edges of the windows. Scattering was initialized by injecting two mL of silicone oil into the mixture. Observation and recording was done by visually inspecting the scattering pattern and capturing images of the wall on which light scattered. Steps above were repeated with different concentrations until light on the wall becomes focused, at which point the indices are matched. To confirm, concentrations below the matched index were also tested, to see that light is indeed more dispersed again. Three trials of this process have been done.

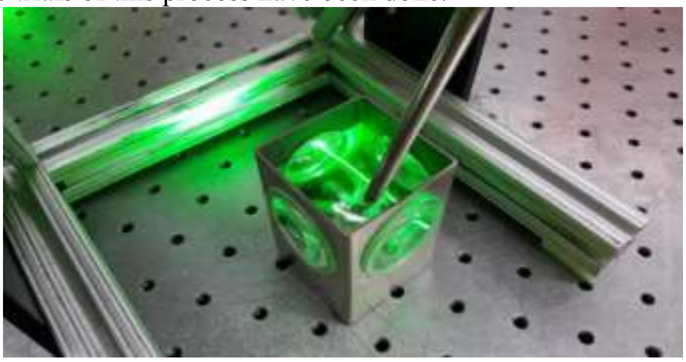

**Figure 1.** Index matching experimental setup with laser turned on.

*2.3. Measuring surface tension between the two fluids*

The pendant drop method is used to find surface tension between the two fluids. This method was chosen because it is a cheap and quick way to test for surface tension. A syringe with a needle that has been bent upwards is secured to the motor mounting frame. The container with 66.7% mass sugar solution is chosen and placed under the needle so that the needle opening is submerged by the sugar solution, concentration and surface tension has little relation. Droplets of the same size were produced by operating the syringe by a fluid dispenser. The droplet was illuminated using a flashlight.

A syringe needle is inserted into one fluid, and then a small amount of the other fluid is pushed out through the needle. A droplet will form on the tip of the syringe, and the geometry of the drop is indicative of the interfacial tension present between the fluids. The following equation [8]

$$\gamma = \frac{\Delta\rho \, g d_e^{\,2}}{H} \qquad (1)\ [8]$$

is used to find surface tension $\gamma$. Delta $\rho$ is the density difference between the two fluids, $d_e$ is the maximum width of the droplet, illustrated in Figure 2. H is a correction factor which is a function of the ratio of $d_s/d_e$, where $d_s$ is the width of the droplet at a height of $d_e$ from the tip of the droplet.

$$\text{Weber Number} = \rho\, v^2\, l / \sigma \qquad (2)\ [9]$$

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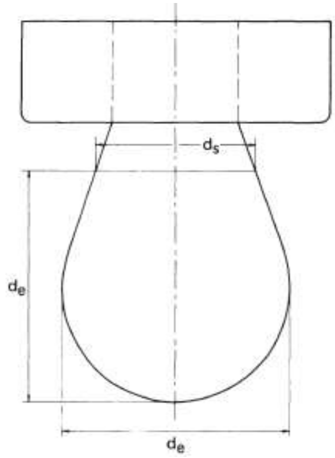


**Figure 2.** Method of measuring dimensions of droplet for surface tension analysis.

## 3. Results and discussion

### *3.1. Index matching of silicone oil and sucrose*

Concentration of the sucrose solution is changed by adding water to the container. Since the experiment is based on refraction of light in different refractive indices, the sucrose solutions need to be completely free of solid sugar grains and other impurities. Initial testing has shown that sugar, especially when creating high concentration (50% mass+) solutions, dissolves very slowly. This is the reason a concentration that is above the expected matching point instead of a concentration that is below the expected matching point is used to start the process. Adjusting concentration by adding water takes much less time, therefore it expedites the experiment. In Figure 3, the two highlighted frames are laser outputs at the most closely matched points.

At the starting concentration of 67.9%, the laser exiting the container casts a scattered shade of green on the wall. Not much changes until the solution gets to 65.6%, where the lit region on the wall starts to become brighter and smaller. At 64.8%, a dot of laser becomes visible to the camera. As the concentration lowers further, the dot becomes small and focused. The laser is most focused at the 64.0% and the 63.5% concentrations. Three trials of this process have shown consistent results. Experimental results from the International Scale of Sucrose Solutions at 20 C show that a solution of roughly 65% would be index matched to the silicone oil used. This discrepancy possibly stems from different testing methods and different purities of sugar used.

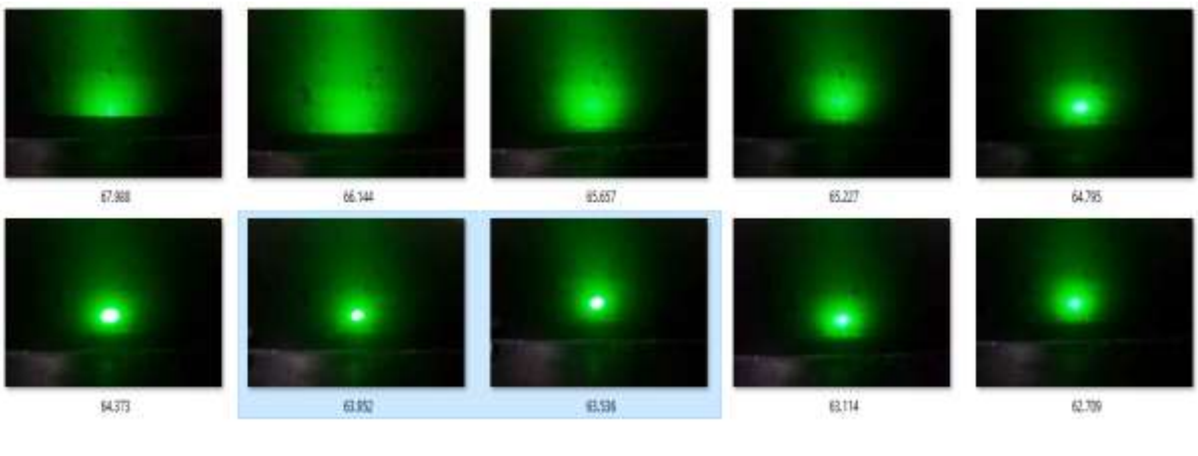


**Figure 3.** Laser exiting the container at different sugar concentrations.

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### *3.2. Surface tension between the two fluids*

The titration process that was carried out during laser scatter testing was also done with an oil droplet. A flashlight was directed at a viewing window on the container and droplets of silicone oil were produced inside various concentrations of sucrose solution. In comparison to laser, this appears to be a less straightforward way to check whether indices are matched, since with the laser method, there is always something to see (focused or scattered light); with a droplet, visual indication of when two fluids are matched is actually when nothing can be seen. The droplet of oil is visible in 67.9% sucrose solution. As the concentration decreases, the bubble is less visible, and it eventually disappears at around 62%. Figure 4 compares when the fluids are index matched and clearly unmatched.

**Figure 4.** Comparison between silicon oil suspended in 62.65% (left) and 59.36% (right) sugar solution.

To calculate the Weber Number for the pseudo spray that is created by this fluid pair, we need to know the interfacial tension between the two fluids. Since the density of sucrose solution that is 1.32g/cm$^3$ (65% by weight) is higher than that of silicone oil (1.05g/cm$^3$), silicone oil will tend to rise to the top of the sucrose solution. This means the capillary needs to have an upwards exit in order for an oil droplet to form. A syringe with a bent needle is used. A picture of the droplet is taken through one of the windows on the container, and the lengths needed by the equation are found through deducing droplet dimensions from the known needle size.

Figure 5 is the picture used to extract droplet dimensions. Width of the widest point, de, and needle diameter were found in pixels. A conversion factor between pixel and meter was obtained by dividing the number of pixels in needle diameter by the actual needle diameter. Now that there is a factor with units of pixels per meter, all pixel values are turned into meters after being divided by this value. Needle diameter is 148 pixels, and its actual diameter is 0.002159 m. The conversion factor is 148px/0.002159m = 68550 [px/m]. This value will differ slightly between each picture depending on how much zoom there was when the picture was taken.

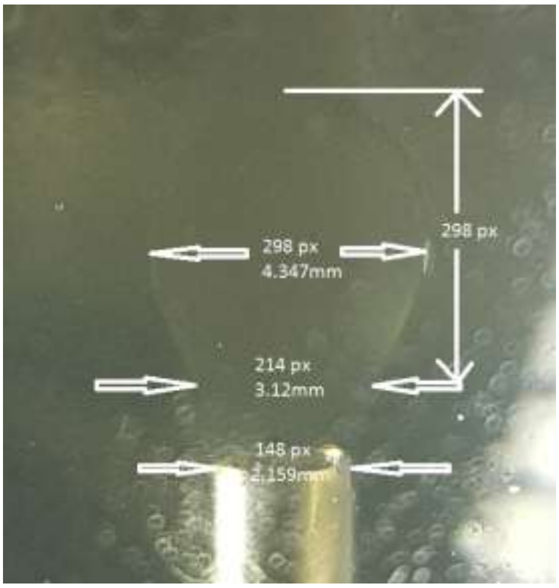


**Figure 5.** Silicon oil droplet with ds and de measured.

Knowing the length of $d_e$, one would find the length of $d_s$ at width of the droplet that is $d_e$ down from the tip. With the droplet shown in Figure 6, $d_e$ is 298 pixels. 298 is added to 86, the Y coordinate of the tip, to arrive at where $d_s$ should be measured. Since the Y axis is inverted in Microsoft Paint, adding to a Y coordinate means moving down the picture. $d_s$ appears to be 214 pixels for this droplet. Table 3 converts these dimensions from pixel to meters, to be used in equation (1) to calculate surface tension.

**Table 2.** ds and de dimensions.

| Dimension | Length [px] | Length [m] |
|---|---|---|
| de | 298 | 0.004347 |
| ds | 214 | 0.00312 |

Equation (1) also requires the difference in density between the two fluids, gravitational acceleration, and a correction factor H. Although H can be derived from dimensions of the droplet, experimental data is available as a function of S, which is $d_s/d_e$.. According to equation (1), the droplet in Figure 4 has a surface tension of 0.08941 [N/m]. As shown in table 3, the sucrose solution/silicone oil pair do not have similar surface tension and Weber number values with an actual fuel/air interface. Ethanol is used as an example.

**Table 3.** Comparison of surface tension and Weber number between different interfaces.

| Interface | Surface Tension [N/m] | Weber Number |
|---|---|---|
| Sucrose Solution/Silicone Oil | 0.08941 | 10943 $V^2$ L |
| Air/Ethanol | 0.02250 | 35066 $V^2$ L |

## 4. Conclusion

Matching the refractive indices of two fluids- one adjustable by concentration, one with a set index- by stirring a mixture of the two and shining a laser through the container has proved successful. Indication that they are matched comes from how the laser exits the container. When the adjustable fluid reaches a concentration where its refractive index matches that of the other fluid, the laser emerged the container as a focused beam, and that happened near the concentration at where they are expected to be matched. This study showed that 63.7% concentration has the best match. Compared to checking for the severity of laser scattering, matching the refractive index with an illuminated droplet of silicone oil inside sucrose concentrations of varying index was not as quick, or as simple to carry out. When moving on to the next concentration, the fluid would need to be stirred manually, detaching the droplet from the needle tip. Creating a new droplet requires a light press on the syringe plunger, which needs to be done very slowly and carefully. Using a new droplet for every concentration also takes away some degree of consistency.

Droplets however were useful in determining surface tension. The surface tension between two fluids is 0.0891 N/m. This knowledge can be used to correct fuel spray behavior predictions, as surface tension and Weber number between actual fuel/air interfaces are not quite the same, which is roughly four times larger than that of ethanol/air. This means using the sucrose/silicone oil fluid pair to model fuel spray will involve some adjustments to be accurate.

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