Final Report: The Effects of the Tadger on the Flow in a Simulated Fuel Delivery System

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1. Introduction

The Tadger is a device that has been shown to reduce pollutant concentrations in the exhaust of spark ignition and diesel engines. Carbon monoxide, unburned hydrocarbons, and particulate matter tend to be reduced over a broad range of vehicle engines spanning passenger to large shipping vehicles. Moderate reduction in fuel consumption, typically ranging from 2 to 5 percent per mile, has also been observed.

The Tadger is a small flow-through device that contains orifices and wake-generating cross flow objects, features that are expected to create turbulence. One might expect that if the inlet flow into the Tadger is already turbulent, the effects of the Tadger on the outlet flow would be small or negligible. Hence the Tadger is expected to alter the turbulence level in the transitional Reynolds number range. Fully-developed pipe flow has been experimentally found to transition to turbulence for Reynolds numbers above 2300, although laminar conditions at higher Reynolds number may be achieved if care is taken to reduce background disturbances. The control of the background disturbances has resulted in an increase of the critical Reynolds number up to 40000.[1] In most applications, the critical Reynolds number will be much lower due to insufficient flow conditioning and the presence of vibrations and noise. For the case of a fuel delivery system in an engine, the pump creates disturbed flow that would be expected to cause turbulent flow above a Reynolds number of 2300, although the presence of a fuel filter acts as a disturbance dampening device that would likely raise the critical Reynolds number.

It is clear that the Tadger causes a change in engine operation, although the physics that control the process are not known. There are various hypotheses that explain how the Tadger operates. Many of these theories rely on the Tadger acting as a turbulence creating device. Within this framework lie several possible mechanisms. One theory is that the turbulence induced by the Tadger causes the gasoline to mix prior to injection, resulting in a more homogenous fuel that may help create a uniform fuel air mixture in the combustion cylinder. Although plausible, the fuel is probably well mixed due to the turbulence created by the pump as well as the return line that results in turbulence and stirring in the tank.

An additional possibility is that turbulence created by the Tadger results in a change in the atomization process. Improved atomization in the form of smaller droplet formation and greater lateral dispersion would result in enhanced evaporation and improved homogenous mixtures of fuel and air in the combustion cylinder prior to ignition. The homogenous mixture is likely to burn more rapidly producing more power per cycle. The drop in unburned hydrocarbons and carbon monoxide is representative of more complete combustion. The reduction in NO_x is more difficult to explain, because higher temperatures are expected if the combustion is faster, and higher temperatures typically results in more NOx through the thermal Zeldovich mechanism.[2] The enhanced work production due to the faster combustion would result in a larger drop in internal energy and temperature later in the cycle, so this explanation is not unreasonable.

A third possible explanation relates to the changes in the pressure distribution within the fuel delivery when the flow is rendered turbulent instead of laminar. The pressure regulator for the fuel delivery system is generally located on the downstream end of the fuel rail, with most engines operating at a fuel pressure of 36 or 41 psig. There are several L/D of pipe length between the pressure regulator and the injectors, hence the pressure at the injector will be slightly higher than the regulator pressure. Increased friction in the flow path between the injector and the pressure regulator will cause the injector pressure to be higher. The friction factor for fully-developed pipe flow transitioning from laminar to turbulent at a Reynolds number of 3000 will approximately double. The altered pressure at the injector would result in a change in the mass flow and momentum of the injector. Additional head losses due to the branching off taps along the fuel rail may be sensitive to the Reynolds number. The electronic control unit (ECU) of the automobile would adjust the injection time to maintain a constant fuel to air ratio.

The objective of the current project was to provide insight into the mechanism responsible for the observed changes in engine performance. The first phase of the project spans the study of the pressure loss and turbulent flow characteristics of the gasoline version of the Tadger. The second phase explored the affects of the Tadger on the gasoline spray atomization for a setup that is qualitatively similar to the fuel delivery system in a spark ignition engine.

2. Pressure Drop Characteristics

The pressure drop features of the Tadger will play an important role in proper sizing of the Tadger for various engine applications. The fuel delivered by the fuel pump in the presence of the Tadger will depend on the losses associated with the Tadger as well as the performance characteristics of the fuel pump. The fuel pressure regulator sets the pressure at one point in the fuel delivery system. If the flow rate drops significantly with the Tadger, the regulator may not be able to hold pressure and likely result in insufficient fuel delivery to the cylinders. Reduced fuel supply to the injectors will impact engine power and operation.

The experimental setup employed to measure the pressure drop through the Tadger is illustrated in figure 1. Air is employed as the working fluid for this setup.

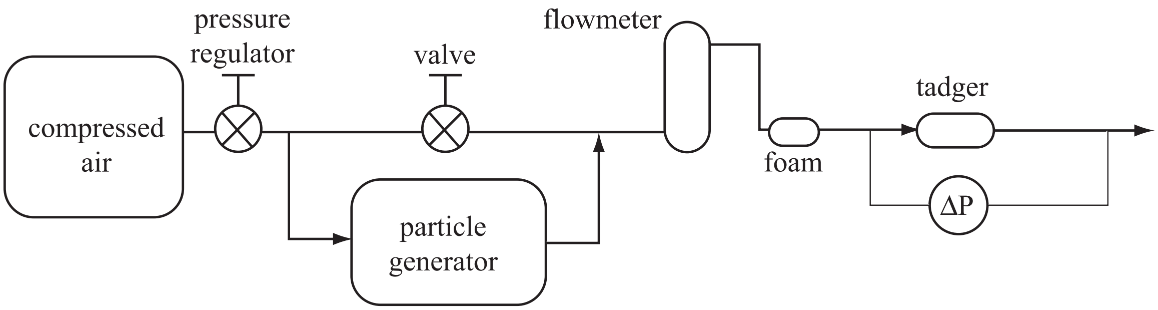

Figure 1: Pressure loss experimental setup

Dimensional arguments suggest that air can be used instead of liquid fuel since the governing physics are characterized by the Reynolds number as long as the Mach number of the air is low, and the fuel would not have reached cavitation conditions. Compressed air is regulated and delivered to a rotameter flow meter. The particle generator is not utilized for the pressure loss experiments. The flow meter will produce turbulence if the Reynolds number based on the hose size is large enough, requiring a flow dampening device to simulate the effects of a fuel filter. A segment of foam is installed in the 3/8 inch diameter hose to damp out flow meter turbulence. The hose connects to the Tadger which has a three foot section of hose on the downstream end. The pressure drop is measured across the Tadger using a pressure gage connected to taps in the hose. The upstream pressure tap is located three feet upstream of the Tadger inlet, while the downstream pressure tap is located three feet downstream of the Tadger to allow the total pressure losses to reach equilibrium. A reference hose without the Tadger having the same length as the Tadger setup was studied to allow the definition of the total pressure loss associated with the Tadger. The independent parameter was the Reynolds number based on the average velocity and hose diameter.

Figure 2 shows the pressure drop in Pascals for the reference case without the Tadger and the case with the Tadger as a function of Reynolds number. Note that the

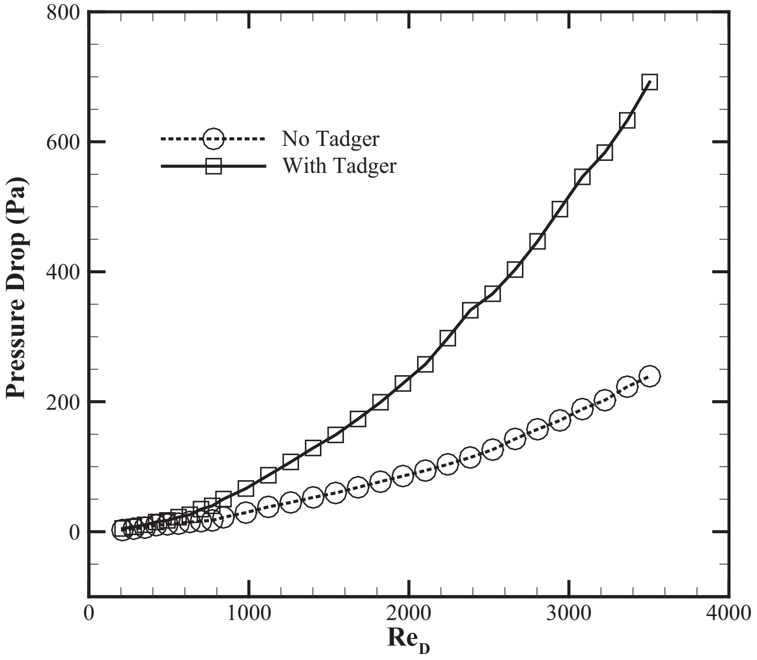

Figure 2: Pressure drop as a function of Reynolds number

magnitudes of the pressure drop would be very different for a case with fuel flowing due to the higher dynamic pressure. It is clear that the Tadger incurs a significant additional pressure drop in comparison to the six foot hose case without the Tadger.

The loss coefficient is defined as

$$k = \frac{\Delta P_T - \Delta P_R}{\frac{1}{2}\rho U^2},$$

where k is the loss coefficient, ΔP_T is the pressure drop with the Tadger, ΔP_R is the pressure drop of the reference case (without the Tadger), ρ is the fluid density, and U is the mean velocity. Figure 3 shows the loss coefficient of the Tadger as a function of Reynolds number. There is strong variation in the low Reynolds number loss coefficient, which settles out to a nominally constant value of approximately 23. For comparison purposes, the pressure loss coefficient for one foot of fully develop pipe flow (3/8 inch inner diameter) at a Reynolds number of 2000 would be approximately 1.35. Hence the Tadger has the equivalent pressure loss of an additional 17 feet of 3/8 inch diameter hose at a Reynolds number of 2000. Note that the pressure drop without the Tadger shown in figure 2 is influenced by the geometry of the static pressure tap hardware which had a smaller diameter than the hose; when the measurements account for losses due to the geometry, the pressure drop agrees with the fully-developed pipe flow expectations. The

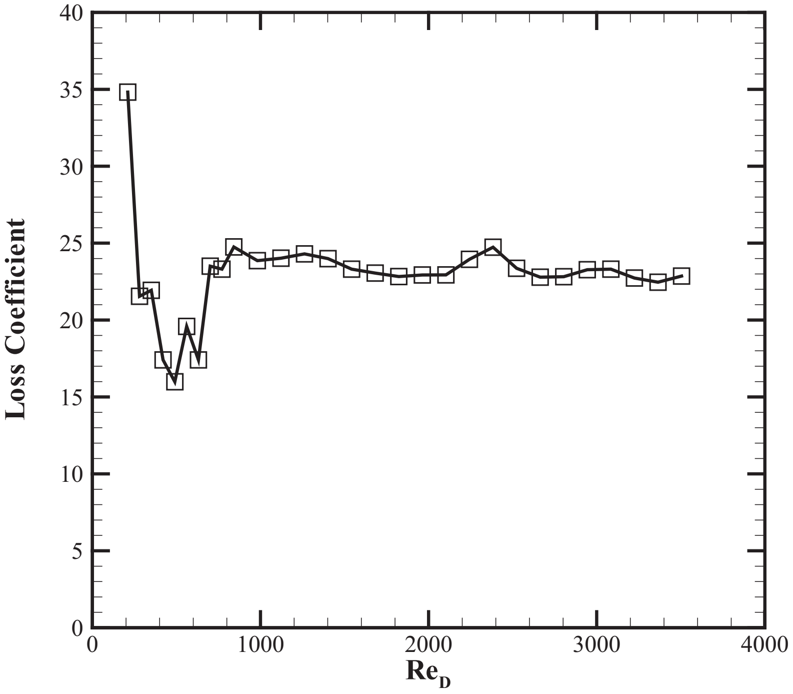

Figure 3: Pressure loss coefficient as a function of Reynolds number

pressure drop characteristics of the Tadger appear to be significant and must be considered for each application.

3. Turbulence Measurements

The experimental setup shown in figure 1 was also utilized to measure the turbulence characteristics induced by the Tadger. Air was once again utilized as the working fluid. The particle generator, required for the PIV technique, generated small olive oil droplets predominantly in the sub-micron range. Particles of this size have sufficiently small inertia that they move at the local gas velocity; hence measurement of the particle velocities can be measured using imaging methods to study the velocity field of the gas phase.

The flow distribution was measured at the inlet of the Tadger, a few inches downstream of the Tadger, and three feet downstream of the Tadger. The PIV technique provides the velocity field in a planar slice through the flow. The plane of measurement can be located in the center plane to within about 1 mm. Figure 4 shows the two-dimensional velocity field measured three feet downstream of the Tadger at Reynolds numbers of 2000 and 3000. A moving reference frame is employed which allows visualization of turbulent fluctuations. At the low Reynolds number, any turbulence created by the Tadger has been dissipated due to viscous action. Note that the level of dissipation will likely be different for fuel due to the different fluid properties. The higher Reynolds number case results in a sustained turbulent flow as shown in the figure.

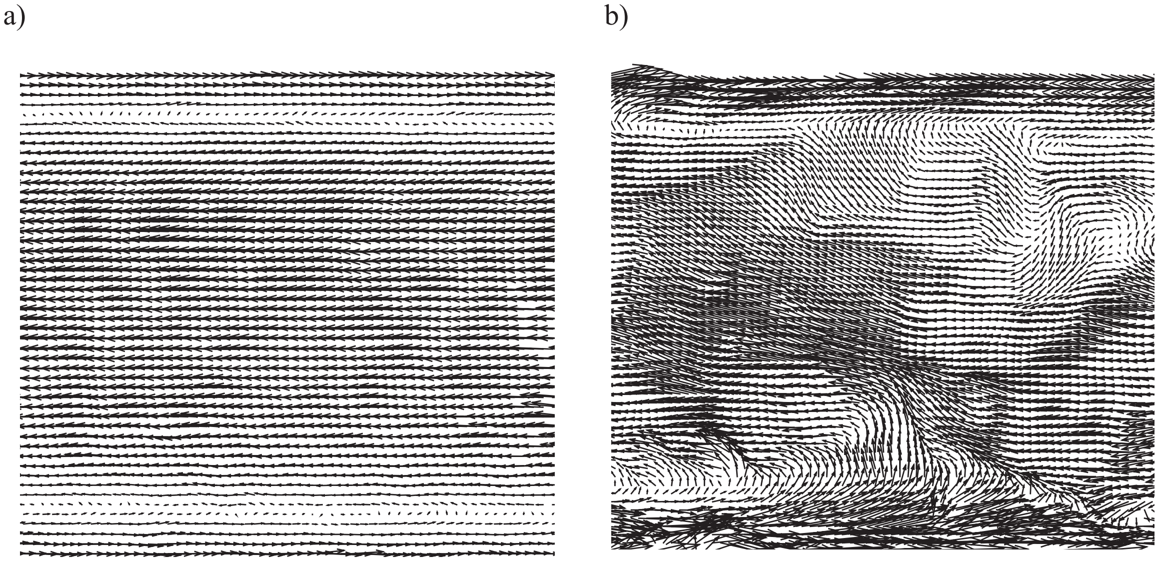

Figure 4: Instantaneous velocity field samples three feet downstream of the Tadger for Reynolds numbers of (a) 2000 and (b) 3000

The PIV technique was used to measure instantaneous velocity fields and subsequent statistical analysis was applied to produce mean and turbulent flow field quantities. Figure 5 shows the mean velocity profile at the Tadger inlet, 6 inches downstream of the Tadger, and three feet downstream of the Tadger, for a variety of Reynolds numbers. The Y axis is the cross stream radial coordinate in mm. The velocity profiles are normalized using the mean velocity as calculated from the measured volumetric flow rates. In general, laminar pipe flow results in a symmetric parabolic velocity profile, while turbulent pipe flow has a flatter mean velocity in the center with larger velocity gradients (and hence shear stress) near the wall. It is seen that the inlet profile is laminar up to a Reynolds number of 3500, where the flow in the experiment naturally transitioned to turbulent flow. The flow six inches downstream of the Tadger generally has a flat profile for all cases. For the three feet downstream distance data, the flow seems to be relaminarizing when the Reynolds number is below 3000. The data for

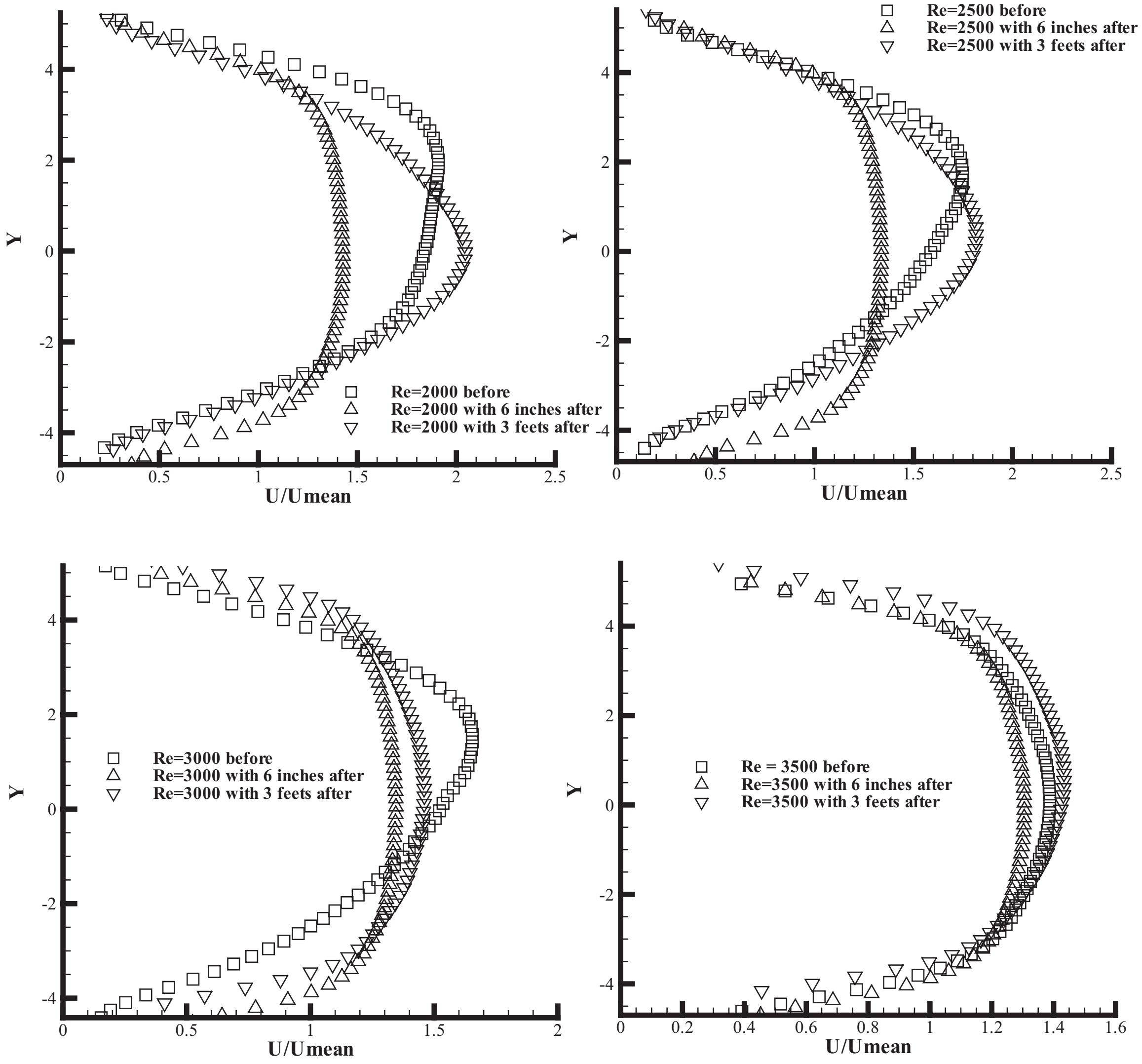

Figure 5: Mean streamwise velocity profiles

the highest Reynolds number of 3500 shows that the Tadger doesn't have a significant effect on the mean velocity profile as would generally be expected since the flow is turbulent entering the Tadger.

Figure 6 shows the root-mean-square of the streamwise velocity fluctuation for the same cases as shown in figure 5; the r.m.s. of the velocity fluctuation represents the temporal variation of the velocity disturbances hence is a measure of the turbulence level.

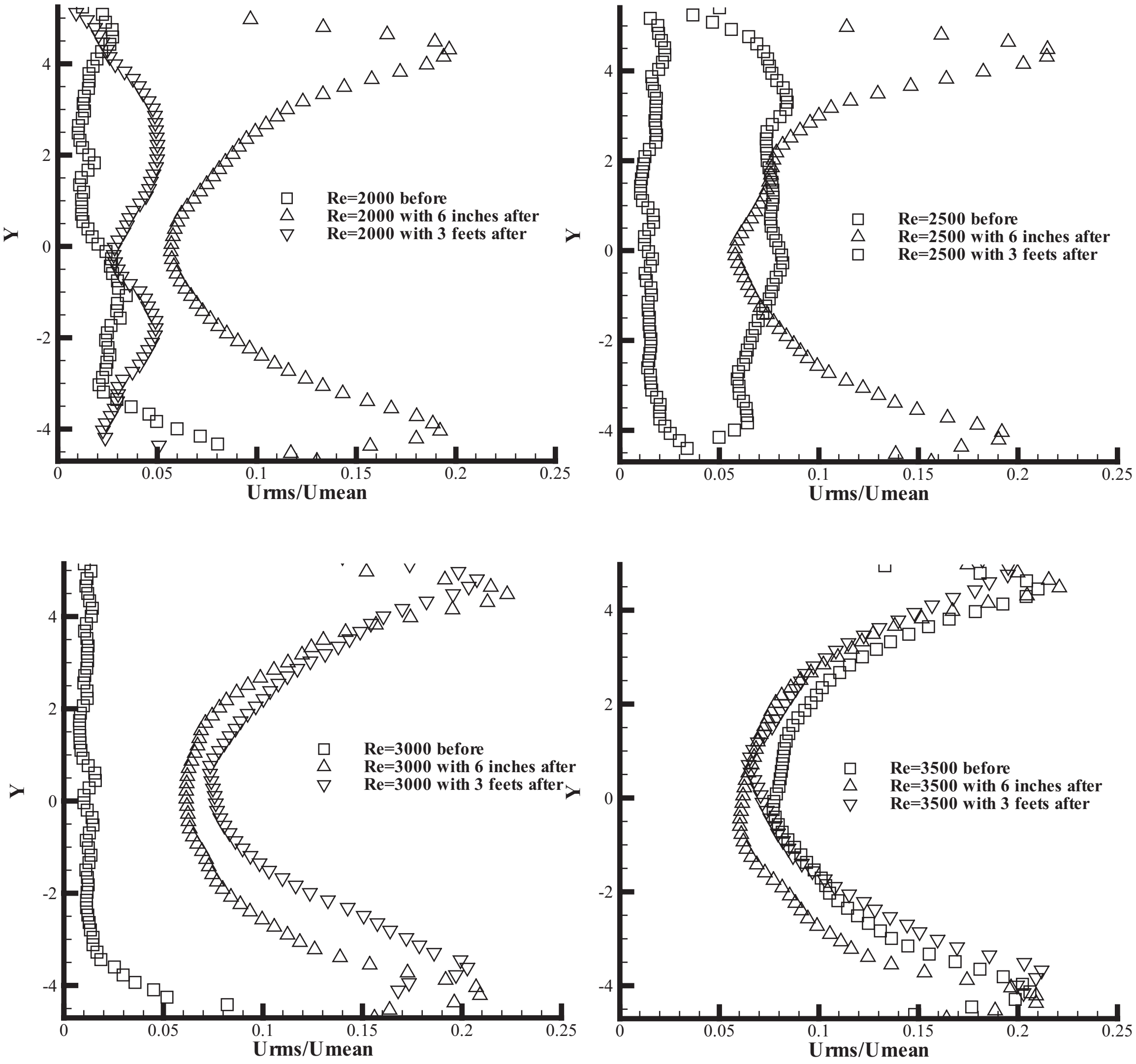

Figure 6: Turbulent velocity profiles

The measurements further support that the flow naturally transitions at a Reynolds number of 3500, as the inlet flow is turbulent at the Tadger inlet, and the Tadger does not seem to have a strong effect on the distribution of the turbulent fluctuations. For Reynolds numbers 3000 and below, the inlet flow is nominally laminar, and the Tadger produces high turbulence levels. The turbulence does appear to be dissipating for

Reynolds numbers of 2500 and below, although complete relaminarization does not occur within the three feet of hose used for the experiment.

4. Spray Characterization

A series of experiments were conducted to study the spatial distribution and velocity characteristics of gasoline sprays under a variety of conditions with and without a Tadger in place. Figure 7 shows a schematic of the test facility that was constructed to study the fuel spray. A Carquest FJ27 fuel injector, compatible with a late 1990s Ford Taurus, was selected as a representative spray nozzle. A National Instruments PCI-6520 Mechanical relay board was employed to control the injector. A 12V DC power supply was connected through the relay to the injector, and a Labview software program was developed to allow for control of the injector. The injector firing rate and duty cycle (i.e. injector period) could be controlled independently. A National Instruments PCI-6251 M series data acquisition card was used to create a digital output signal for control of the imaging system. A digital delay generator was used to allow images to be collected at a controlled phase relative to the injection timing. All measurements were taken with 10 Hz injector firing rate, 10 ms injection time, and a pulse delay for the PIV such that images were collected near the middle of the injection cycle. Imaging was done approximately 15 cm downstream of the injector exit to allow for primary atomization to occur prior to the measurement region. The image captures a nominal 4 x 4 cm region of the spray, and contains the full width of the spray at this downstream location.

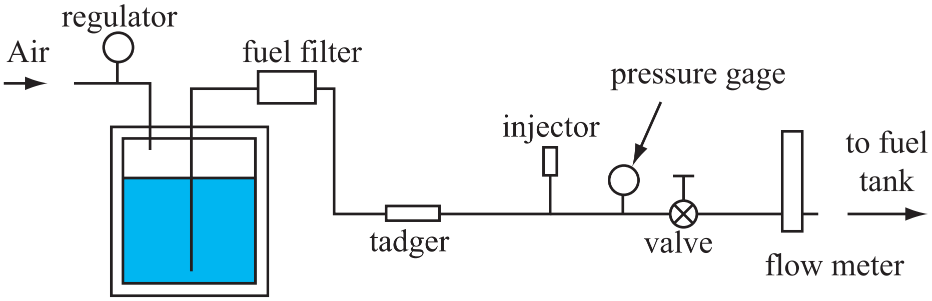

Figure 7: Experimental setup for the spray PIV studies

In order to minimize disturbance effects from the main fuel pump that we employed during preliminary tests, an alternative fuel pumping system was developed. A small plenum was filled with gasoline, and compressed air was used to drive the fuel through the system using a pressure regulator. This method allowed for a smooth main flow to be developed without pulsations due to the pump. A valve downstream of the injector was used to control the fuel pressure. A rotameter was used to measure the fuel flow rate in the main fuel line. A thermocouple near the injector was used to measure the fuel temperature.

The experimental setup includes a large number of geometrical and operational parameters. The following geometrical parameters have been identified as independent variables:

1. d, the fuel hose inner diameter, held at 3/8" during the tests
2. L/d between the Tadger and fuel injector branch
3. L/d between the fuel injector and the branch from the main fuel line

The following operational parameters have been identified as independent variables:

1. Fuel pressure (ranged from 30 to 45 psig, most measurements taken at 40 psig)
2. Main fuel volume flow rate (ranged from 1 to 20 gallons per hour)
3. Fuel dynamic viscosity (dependent on fuel composition and fuel temperature)
4. Fuel density (dependent on fuel composition and fuel temperature)
5. Fuel vapor pressure (dependent on fuel composition and fuel temperature)
6. Fuel temperature near the injector
7. Injector fuel flow rate (dependent on injector firing rate and injection time)

The objective of this phase of the project was to provide experimental data to either validate or disprove various working hypotheses of the Tadger. The primary hypothesis at the beginning of the project was that the Tadger produced turbulence that altered the fuel spray through interaction between the atomization process and the turbulence in the fuel line. The extensive *prior* testing on the Tadger performance on actual engines provide a general set of observations:[3, 4]

1. The Tadger works for fuel injection ***and carburetors***
2. The Tadger works for gasoline and diesel engines
3. The Tadger has shown an effect located both upstream and downstream of the fuel filter
4. The Tadger was effective even when the fuel line distance between the Tadger and the fuel rail was very large

; although these observations may or may not be general, they provide an important backdrop for proposed operating principles for the Tadger.

Significant preliminary attention was focused on exploring the affect of the Tadger on the fuel spray due to turbulence effects produced by the Tadger. The PIV method allows for the measurement of the droplet velocities, while the images provide information on the dispersion and a qualitative indication of the droplet size. Measurements were made for a range of fuel flow rates with and without the Tadger to determine if the documented turbulence effects appear to alter the spray. Figure 8 shows the mean image intensity profile for a variety of main fuel line flow rates, with and without the Tadger. The data in figure 8 is integrated along the streamwise direction to reduce precision uncertainty and provide an average measure of the spray distribution across the 4 cm streamwise length of the imaging region. The x coordinate is the cross-stream distance in terms of pixels, with each pixel being equivalent to approximately 37 microns in the physical space. The mean intensity is sensitive to the number and size of droplets. As can be seen from the figure, there is nominally no affect of the Tadger on the mean spray image. The velocity data collected by the PIV system showed that the droplet velocities were nominally unchanged as the main fuel flow rate changed and the Tadger was installed/removed.

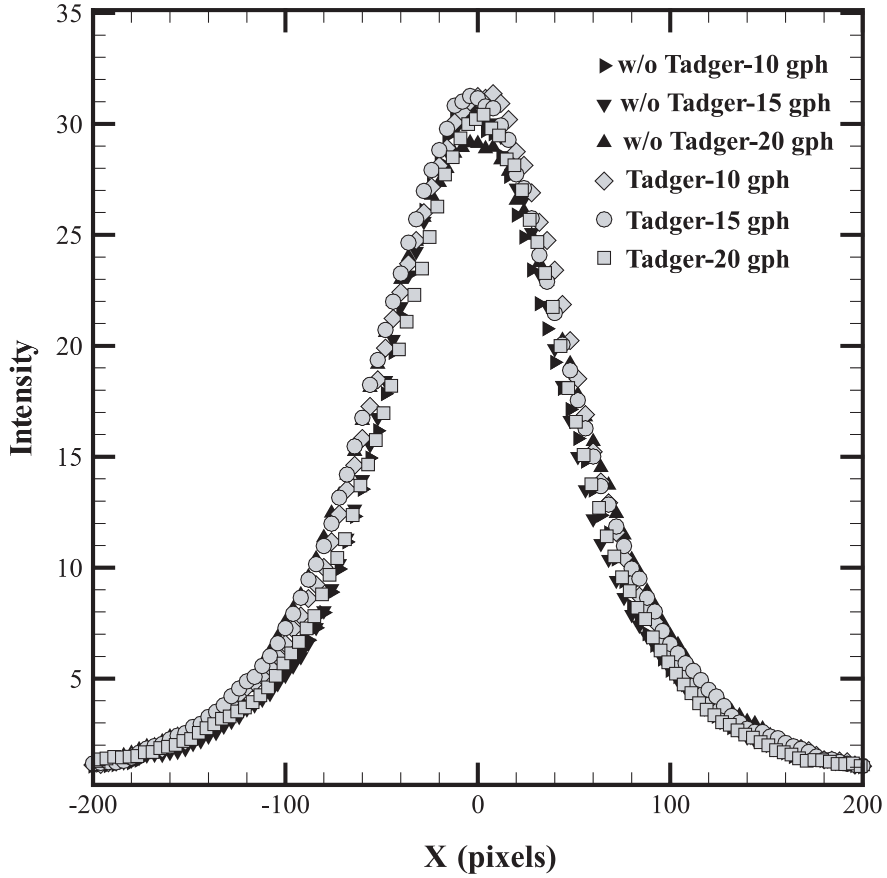

Figure 8: Mean image intensity profiles for various fuel flow rates and with and without the Tadger

In hind sight, the observation that turbulence in the fuel line does not appear to alter the spray is consistent with scaling arguments. First of all, the velocity in the fuel line is much slower, by a factor of approximately 1/100 or less than the velocity in the fuel injector nozzle. Hence fluctuations in the pipe are going to be extremely weak and are not likely to impact the atomization process, especially with consideration of other disturbances such as engine vibration. Additionally, the disparity in length scales for the turbulence in the fuel line and the injector nozzle are at least an order of magnitude apart. The velocity and length-scale mismatch would disrupt interactions between the turbulence and the atomization process.

An observation made during the fuel tests resulted in an alternative mechanism to explain the effect of the Tadger. With slightly warm fuel, it was found that the temperature downstream of the injector was cooler with that Tadger in relation to the case without the Tadger. This observation lead to a new hypothesis; the Tadger causes enhanced preheating of the fuel prior to delivery to the injector. This preheating is not due to turbulent dissipation, which would have a negligible effect, but due to enhanced heat transfer between the fuel and the fuel delivery system which are likely to be at different temperatures due to the heating within the engine compartment. The turbulence created by the Tadger will enhance convective heat transfer in the fuel line, including the fuel rail and the fuel injector. Additionally, the Tadger itself could be viewed as a heat exchanger. It is made out of aluminum and is placed in the engine compartment and is likely subject to heating from the engine. The internal geometry of the Tadger also has fin-like features that will efficiently transfer heat, and are found in most heat exchangers. This explanation was more consistent with the observations that: 1) the Tadger works on fuel injection and carburetors, 2) the Tadger was effective when placed upstream of the fuel filter.

A study was focused on determining the effect of fuel temperature on the fuel spray. The fuel spray is expected to be sensitive to the fuel temperature due to variation of properties with temperature. The vapor pressure increases with temperature for liquids, hence a higher temperature fuel will promote faster evaporation. Viscosity, density, and surface tension of the fuel will also depend on temperature, resulting in an alteration of the spray parameters, the Reynolds number and the Ohnesorge number.[5] Additionally, as the fuel temperature increases, the potential for cavitation inside the injector nozzle increases, having a drastic effect on the atomization process.[5, 6]

A series of tests were conducted to determine the effect of fuel temperature on the spray for a fuel pressure of 40 psig. Figure 9 shows the mean image intensity integrated in the spray direction for several data sets having either high or low fuel temperature. The x coordinate is the coordinate that is perpendicular to the spray direction. These profiles are dominated by the larger droplets that saturate the digital camera sensor. The higher intensity near the centerline of the spray is caused by the higher probability of finding droplets near the axis of the spray. The results show that the mean image intensity along the spray axis is higher for the higher temperature fuel. The peak intensity is 30% higher for the hot fuel compared to the cold fuel. This is an indication of a different droplet size distribution within the spray. The observation is consistent with the concept that a warmer fuel results in a size distribution shifted to have higher probability of somewhat smaller droplets. Note that the current approach does not detect tiny droplets, hence only changes in the larger droplet characteristics would be captured.

In order to further substantiate that the mechanism of the Tadger is related to heat transfer enhancement, a small number of tests were done using warm fuel and the measured temperature drop across the Tadger and the injector assembly. A setup was constructed to measure the temperature change across the tadger and the simulated fuel rail under a variety of flow rates. Warm fuel was used in this case, at nominal temperature of 105 ºF. The temperature drop across the tadger was much larger when the Tadger was present; the temperature drop measurements are listed in Table 1. This result supports the hypothesis that the Tadger promotes enhanced heat transfer.

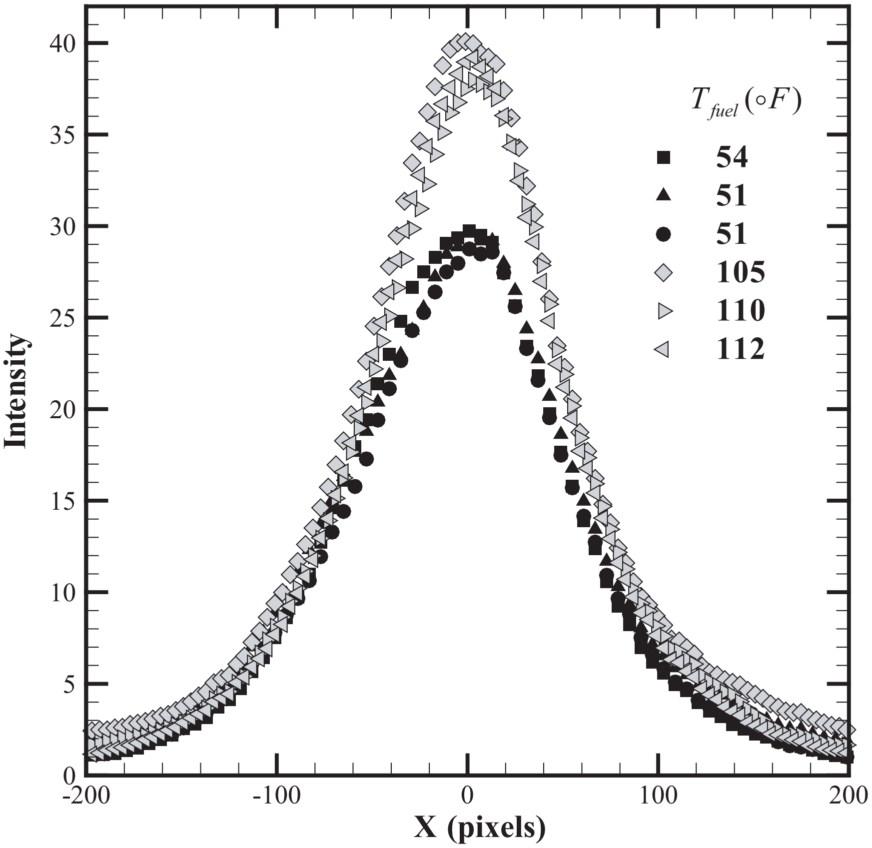

Figure 9: Mean image intensity profile for hot and cold fuel

Fuel flow rate (gph)	Temp. drop Tadger + fuel rail (ºF)	Temp. drop fuel rail (ºF)
2	6.4	2.9
4	11.9	6
6	13.6	10.5

Table 1: Summary of temperature drop tests

The values listed in Table 1 are only to illustrate the relative effect of the heat transfer.

5. Conclusions

Various measurements have been conducted to document the pressure drop, turbulence generation, and spray characteristics due to the Tadger. It was found that the Tadger has no measurable effect on the mean spray pattern for a fixed fuel temperature. It was discovered that the Tadger enhances heat transfer when there is a temperature difference between the fuel and the ambient environment. Measurements of the fuel spray at different temperatures show an effect of fuel temperature that suggests larger numbers of smaller (measurable) particles are present for higher fuel temperatures. A new mechanism is proposed for the operation of the Tadger that is based on heat transfer. The Tadger promotes enhanced heat transfer through convection through the Tadger as well causing turbulent transition at intermediate Reynolds numbers. This explanation is the most robust and consistent with the various observations that the Tadger has shown to have impact in spark ignition and diesel, as well as fuel injection and carburetor fuel systems. A test was done that indicates that the Tadger does enhance heat transfer between the fuel and the ambient environment.

6. References

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