Visualization of low-level swirl effects in fuel injection sprays

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Abstract

This work presents results from the STATICS[1] spray rig, an adjustable single-orifice laboratory spray with carefully designed inlet parameters, employed here to produce a steady non-cavitating spray. This spray system can be adjusted to achieve a range of conditions which are representative of liquid breakup near or within the high-pressure atomization regime common to fuel injection applications. By isolating the developing spray from cavitation disturbances, other factors which impact the form of the liquid breakup are more readily distinguished and experimental results can be generated under conditions which are readily accessible for numerical spray modeling efforts.

A common feature observed in shadowgrams and ballistic images of pressure atomizing plain-orifice sprays is an apparent spreading of the liquid mass as it moves downstream. This can give the impression that the jet is growing even as some regions of the flow shed mass into the surrounding environment in the form of ligaments and droplets. However, in the case of the steady, unperturbed spray arrangement this characteristic spreading is virtually absent from the high-speed shadowgram results, indicating that some aspect of the flow which is significant to the spray formation may be missing from the tailored inlet conditions.

Recent large eddy simulation (LES) results for interior flows in transient fuel sprays indicate that large vortices are created inside the injector body in response to turbulent upstream conditions. These coherent vortical structures are expected to break down as the fuel flow moves through the narrow geometry preceding the injector orifice. However, in most cases a non-zero mean rotational velocity persists in the bulk flow as it exits the nozzle, potentially generating significant changes in the character of the liquid breakup which can be observed in the spray morphology.

The inlet conditions of the STATICS spray rig were adjusted to allow a comparative study of the effects of low-level swirl on the character of the spray. Here, the same spray conditions were run with a swirled inlet condition effected by adding a swirl trip upstream of the orifice. In addition, supplementary measurements of a single-hole, plain-orifice diesel fuel injection spray were undertaken to provide a qualitative comparison with a standard common-rail diesel fuel injection condition, which could be examined for evidence of similar swirl characteristics. In this case, high-speed shadowgraphy with front-lighting was used to visualize the spray edges and highlight salient surface texture which could then be correlated to estimate swirl imparted to the liquid jet.

Introduction

Spray formation and liquid breakup encompass a wide range of coupled physical interactions with widely varying spatial and temporal scales. This multi-scale, transient, and semi-chaotic nature of fluids in extreme dynamic conditions is precisely what makes them interesting and vitally useful for any number of scientific and industrial applications. From a global economic and environmental perspective, understanding and improving high-pressure sprays for the delivery and dispersal of liquid fuels used in combustion presently ranks among the most urgent of scientific pursuits. To this end, it is essential to identify and explore curious or unexplained behavior observed in sprays. One such interesting and in some respects counterintuitive feature of sprays at elevated injection pressures is the apparent spreading observed in the liquid plume as it exits the orifice. Figure 1 shows an ultrafast shadow image taken of a plain-orifice diesel fuel injection event that typifies this apparent growth of the main jet.

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[1] Steady Trip Adjustable Turbulence, Inlet, Cavitation, and Swirl

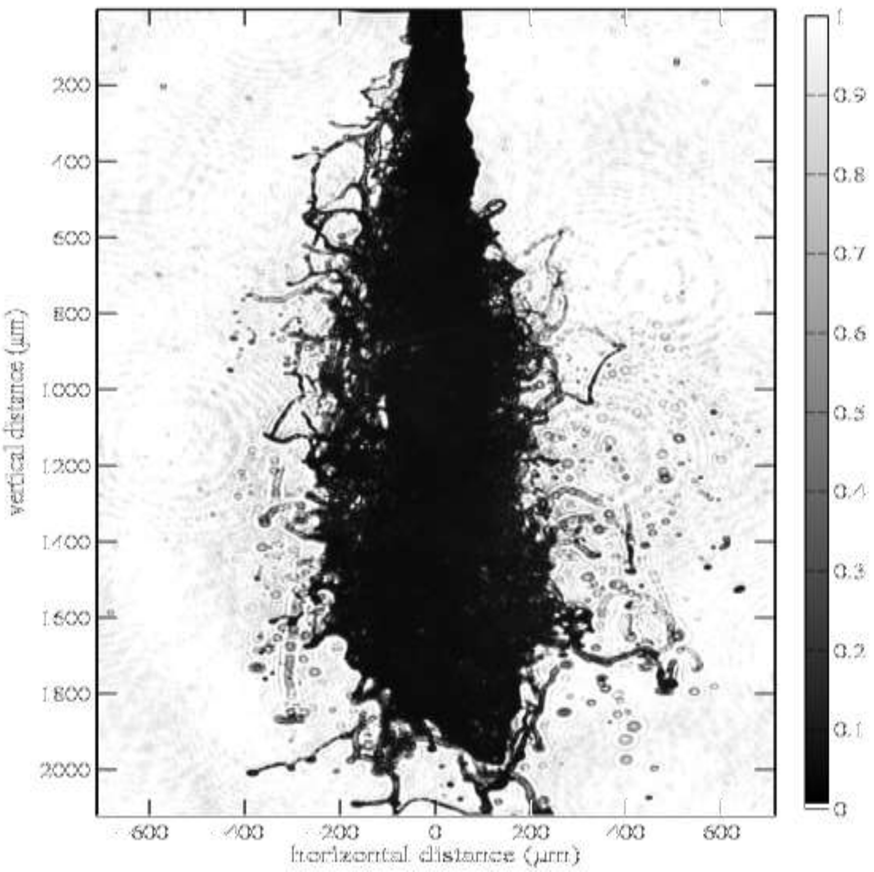


Figure 1. Image result showing the apparent spreading of the spray plume. The image shows a diesel jet issuing from a 113 µm plain-orifice test injector into ambient air, 18 µs after start of injection, with injection pressure = 60 MPa.

This is a common feature of shadowgrams and ballistic images which gives the impression that the jet is growing even as some regions of the flow shed mass into the surrounding environment in the form of ligaments and droplets. However, over the course of our study conditions the shadowgrams of the unperturbed spray arrangement showed virtually no trace of this characteristic spread. This would seem to indicate that some aspect of the flow which is significant to the spray formation may be missing from the tailored inlet conditions of the unperturbed STATICS spray.
Figure 1 shows a diesel jet expanding into ambient air under flow conditions characterized by a Mach number less than 0.24. Given that liquid compressibility effects are generally known to be negligible in flows with Mach numbers as high as 0.3 or 0.4, it is unlikely that this characteristic spread of the high pressure spray can be due to divergent expansion of the injected fluid as it moves into the low pressure surroundings. Likewise, a conservative estimate of the compressibility indicates an expansion of less than 0.1% in the liquid volume [1].

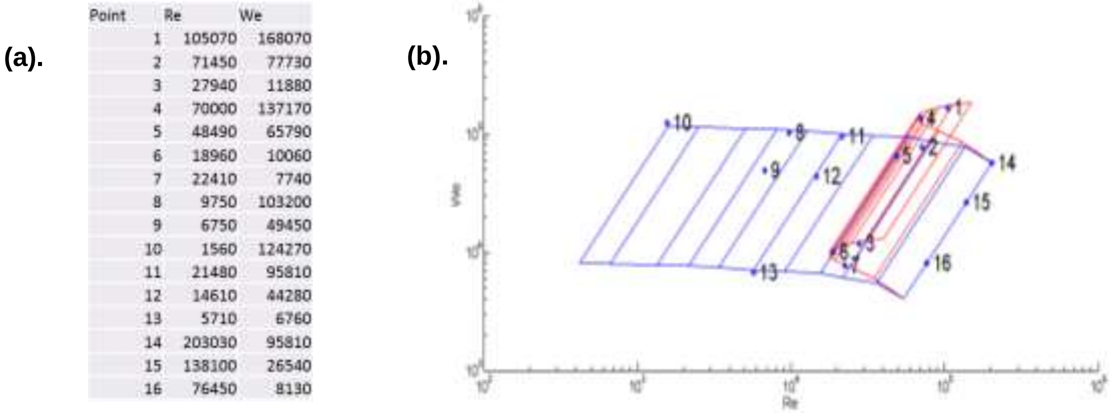
Recent large eddy simulation (LES) results for interior flows in transient fuel sprays indicate that large vortices are created inside the injector body in response to turbulent upstream conditions [2]. These coherent vortical structures are expected to break down as the fuel flow moves through the narrow geometry preceding the injector orifice. However, in most cases a non-zero mean rotational velocity persists in the bulk flow as it exits the nozzle, potentially generating significant changes in the character of the liquid breakup which can be observed in the spray morphology.

Thus, one plausible explanation for this behavior is that the lower injection pressures, increased scale of the test injector, and uniformity of the upstream flow produce very little rotational velocity in the bulk flow, and that this rotational motion is a significant factor in atomizing the liquid jet. There is some evidence that even small amounts of swirl can significantly increase the turbulence intensity in plain-orifice sprays [3] and heavily influence the dynamics of turbulent flows [4].

Material and methods

This work presents results from a qualitative study of a non-cavitating single-orifice laboratory spray at a range of conditions which compare the spray morphology obtained with and without swirling inlet flows. The STATICS spray rig used in this work is a steady spray system designed with adjustable controlled inlet conditions that allow for varying levels of input turbulence, inlet flow, cavitation, and swirl by means of removable flow trips which can be placed upstream of the nozzle orifice. The system is designed to achieve a range of Reynolds and Weber number conditions which are representative of liquid breakup near or within the high-pressure atomization regime common to fuel injection applications. The range of spray conditions which can be covered by the system in its current configuration using test fluid mixtures of water, ethanol, or dipropylene glycol are shown in Fig. 1, accompanied by table detailing the conditions explored in the current work.

The inlet conditions chosen for comparison data were selected to promote moderate turbulence in the inlet while taking care to avoid the any occurrence of cavitation upstream of the orifice. The removal of cavitation was desirable in this case to simplify the flow in order to more readily identify other factors which impact the form of the liquid breakup.



Point	Re	We
1	105070	168070
2	71450	77730
3	27940	11880
4	70000	137170
5	48490	65790
6	18960	10060
7	22410	7740
8	9750	103200
9	6750	49450
10	1560	124270
11	21480	95810
12	14610	44280
13	5710	6760
14	203030	95810
15	138100	26540
16	76450	8130

Figure 2. (a). Reynolds and Weber number conditions for run conditions measured in this work. (b). Regime map of Weber number versus Reynolds number showing the range of conditions covered by the current STATICS spray rig configuration. The red portion of the plot indicates conditions achieved using ethanol or ethanol/water blends, while the blue areas indicate conditions reached with water or dipropylene glycol mixtures.

The swirling inlet flow is achieved by the addition of a swirl trip upstream of the nozzle orifice (see Fig. 3). The combined axial and rotational flow in the inlet can be described in terms of a geometrically defined swirl number, S, as formulated by Syred et al. [5]:

$$S = G_{\mathrm{ang}} / (G_x \times r) \tag{1}$$

where G_{ang} is the axial flux of angular momentum, G_x is the axial thrust, and r is the radius of the trip. If the inlet flow is relatively even such that the axial and rotational components of the flow are related to the blade angle as *tan α* = (*U / W)*, then the axial flux of angular momentum in the annular section can be written as:

$$G_{\mathrm{ang}} = 2\pi\rho \int_{R_c}^{R_b} U_a (U_a \tan\alpha) r^2 \, dr \tag{2}$$

where U_a is the mean axial velocity on supplied through the swirl annulus, R_c is the inner core radius, and R_b is the outer boundary radius. Thus, the effective geometric swirl number can be expressed in terms of the vane angle, α, trip radius, R, and the center to annular mass flux ratio, m:

$$S = \frac{2}{3} \tan\alpha \frac{1 - R^3}{1 - R^2 + (m^2(1/R^2 - 1)^2)R^2} \tag{3}$$

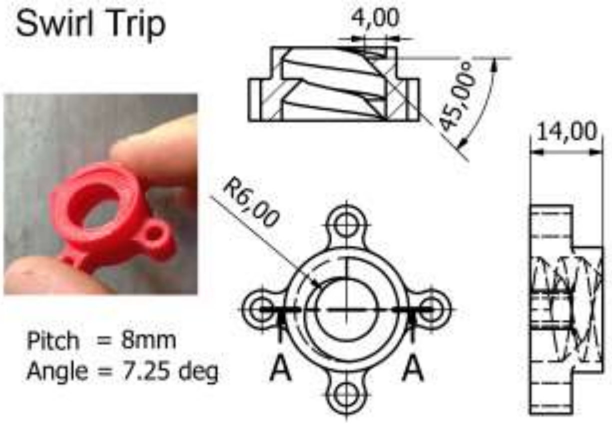


Figure 3. Flow swirler trip insert designed for the STATICS spray rig.

The swirler trip depicted in Fig. 2 features a vane angle of 7.25 degrees, inner and outer radii of 6 and 4 mm, respectively, with a total depth of 14 mm. Using Eq. 3 and estimates of the flow conditions, the swirl number of the STATICS spray rig with the swirl trip is estimated to be between 0.86 and 1.0.

Results and Discussion

A selection of results showing composite views of the unperturbed (no swirl) STATICS spray rig which were compiled from high-speed shadowgraphy measurements are shown in Fig. 4. Here the top, center, and lower boxes in each of the four views represent disjoint shadowgram results for near-nozzle, 10, and 20 nozzle diameters downstream, respectively.

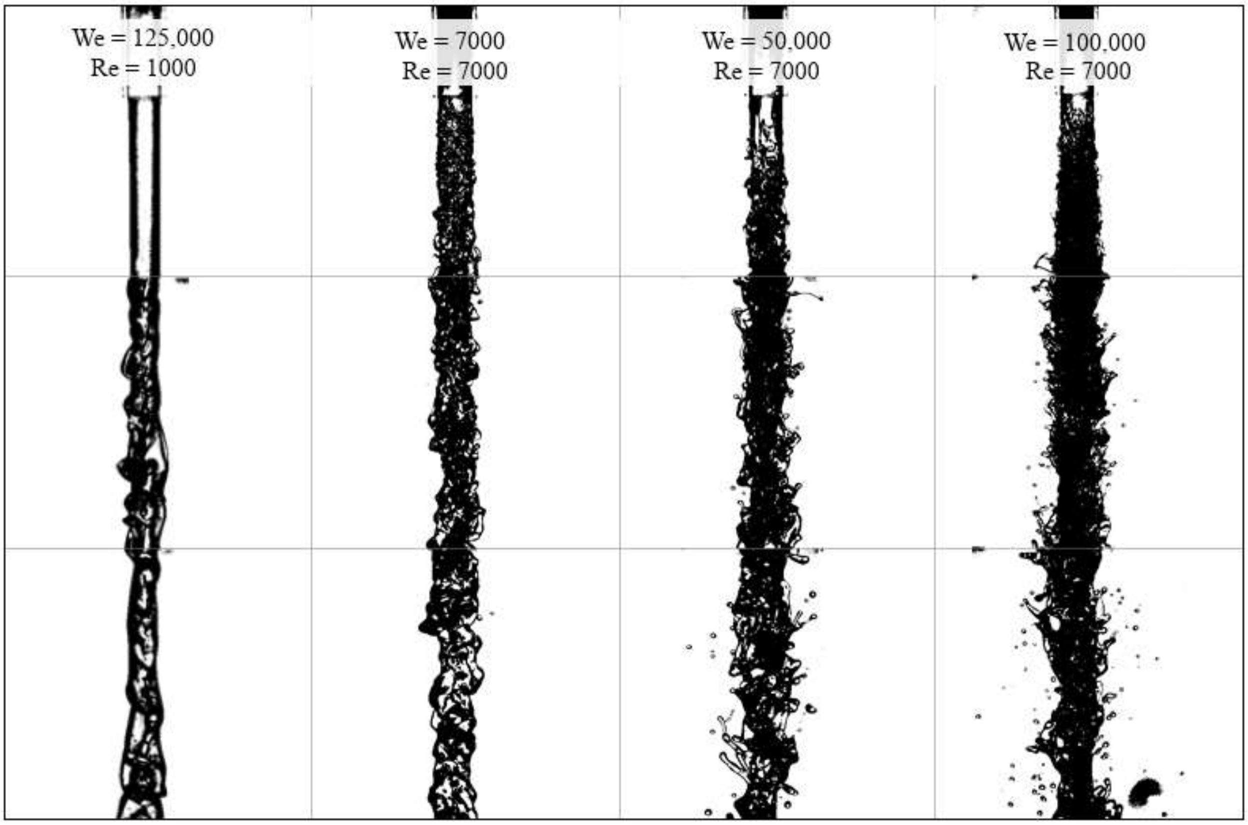


Figure 4. Composite shadowgram results showing non-cavitating (no-swirl) test spray. Spray maintains roughly linear trajectory without the characteristic spread observed in shadowgraphy of high-pressure fuel injection sprays.

The significance of low-level swirl effects for establishing the characteristic expansion observed in the morphology of atomizing sprays is supported by the preliminary imaging results obtained in the swirler trip modified STATICS spray rig. In this case, additional swirl has been added to the interior nozzle flow, resulting in increased liquid breakup and spreading of the jet which is consistent with the apparent expansion observed in atomizing fuel injection sprays. Figure 5 (a). and (c.) show near-field and developed flow shadowgrams for the unperturbed test injector, together with the low-swirl case shown in (b.) and (d.).

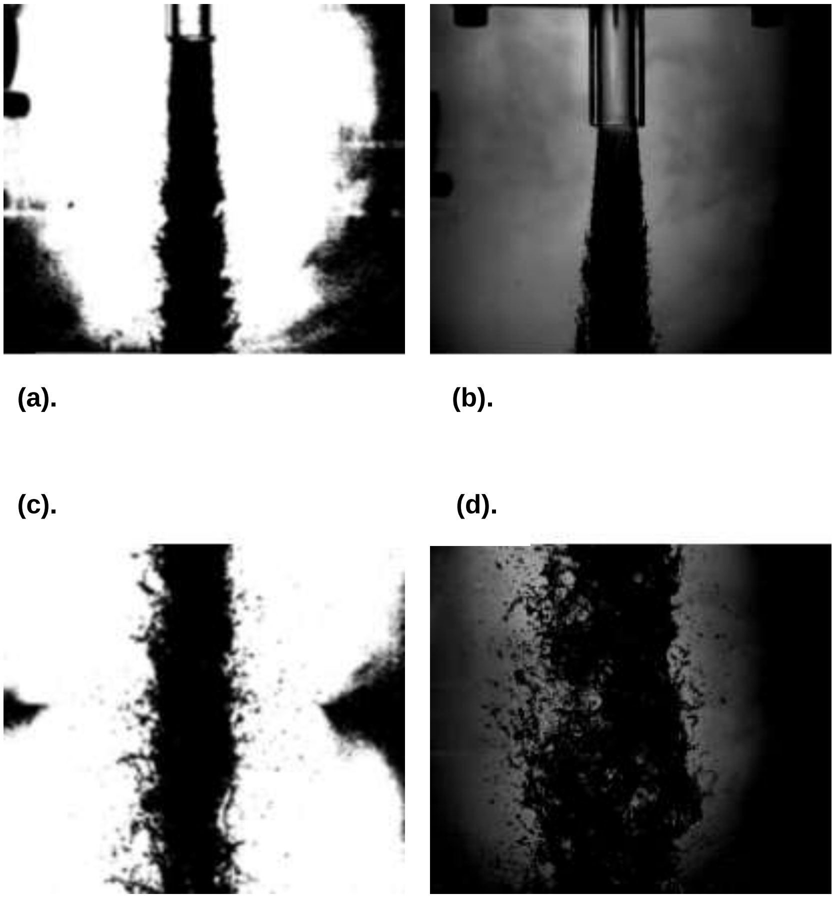


Figure 5. Shadowgrams of non-cavitating test spray showing near nozzle and fully-developed flow for unperturbed and swirling flows (Re=100k, We=120k): (a). near-nozzle, no swirl; (b). near-nozzle, with swirl; (c). developed, no swirl; (d). developed, with swirl.

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