

Air-Entrainment in Wall-Jets Using SLIPI in a Heavy-Duty Diesel Engine

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ABSTRACT

Mixing in wall-jets was investigated in an optical heavy-duty diesel engine with several injector configurations and injection pressures. Laser induced fluorescence (LIF) was employed in non-reacting conditions in order to quantitatively measure local equivalence ratios in colliding wall-jets. A novel laser diagnostic technique, Structured Laser Illumination Planar Imaging (SLIPI), was successfully implemented in an optical engine and permits to differentiate LIF signal from multiply scattered light. It was used to quantitatively measure local equivalence ratio in colliding wall-jets under non-reacting conditions. Mixing phenomena in wall-jets were analyzed by comparing the equivalence ratio in the free part of the jet with that in the recirculation zone where two wall-jets collide. These results were then compared to ϕ predictions for free-jets. It was found that under the conditions tested, increased injection pressure did not increase mixing in the wall-jets. Comparisons with free-jet predictions further indicated that mixing in wall-jets is less effective than in free-jets for identical conditions and downstream distances. The confined nature of the wall-jet in the optical engine is suspected to be the reason for these observations. A rapid leaning-out of the jet after end of injection was observed for all cases, but this enhanced mixing was not transmitted to the wall-jet.

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INTRODUCTION

Soot formation in diesel engines is highly related to the local fuel-to-air equivalence ratio between fuel and air in the fuel jet. Generally, the more air that is entrained in a diesel jet, the weaker the soot formation is [1]. Extensive research has been performed on air-entrainment in fuel jets at high injection pressures leading to a general understanding of the mechanisms involved [2,3,4,5,6]. The main focus of these previous works has been to estimate the local stoichiometry in the jet at the lift-off region in order to predict the soot formation tendency. This relies on the observation that oxygen-entrainment in the jet downstream of the lift-off region is decreased compared to the upstream region of the jet, due to the presence of the high temperature diffusion flame that surrounds the jet and consumes most of the entrained oxygen. However, oxygen entrainment is also important in the parts of the jet that are downstream of the lift-off region to ensure efficient oxidation, which relies upon access to O₂ and OH radicals [7].

Furthermore, the diesel jet geometry is complex due to the presence of the bowl-wall in the downstream region, typically 40 mm from the nozzle in a heavy-duty diesel engine. When

the jet reaches the bowl wall it is diverged into wall-jets. As the wall-jets travel along the bowl wall, they are confined between the piston floor and the firedeck, roughly 15 mm apart at top dead center in a heavy-duty diesel engine. When two neighboring wall-jets eventually collide they form a recirculation zone, as will be shown later in the results section.

Although most air-entrainment investigations in combustion vessels are performed on free jets, Bruneaux *et al.* placed a flat wall about 30 mm downstream of the nozzle to study the air-entrainment in an impinging fuel jet [8]. Results showed an increased air-entrainment after the wall impact compared to the free jet. Furthermore, higher equivalence ratios were observed in the free-jet just before the wall impact. At an injection pressure of 1500 bar, these two effects were equally strong, thus canceling one another and leading to the same total-air-entrainment as in a free-jet. However, at 2000 bar injection pressure the air-entrainment after the wall impact was substantially enhanced, resulting in higher total air entrainment as compared to a free-jet.

The current study aims to determine if similar trends can be observed in a diesel engine. Two hypotheses are investigated. The first one is that enhanced mixing in the

wall-jet and recirculation zone could be due to increased turbulence. Increasing injection pressure would increase turbulence in the wall-jet as an effect of higher impact momentum and higher average flow speeds. If this hypothesis was to be confirmed, the same effect would be observed in the optical engine as in the combustion vessel used by Bruneaux *et al.* [8].

The second hypothesis is that the effects observed in the combustion vessel are mostly due to an increase in surface-area of the fuel-jets after interaction with the flat wall. A larger area available for mixing would then imply a greater air-entrainment rate. If this is a major mechanism behind the trends observed in the combustion vessel the effect will be substantially weaker in the engine, as the jet is more confined than in a combustion vessel and the surface area of the jet cannot increase as much.

In order to test the above hypotheses, experiments were carried out in an optical engine where the wall-jet is expected to behave essentially as it does in a real engine. Injection pressure and inter-jet angle were varied to observe their effects on air-entrainment in the wall-jet. The local equivalence ratio was measured using quantitative laser induced fluorescence (LIF) of a fuel tracer (acetone). A novel technique called Structured Laser Imaging Planar Illumination (SLIPI) [9,10,11] was used in order to remove multiply scattered light from the actual fluorescence signal.

EXPERIMENTAL SETUP

Optical Engine and Operating Conditions

The presented investigations were performed on a six cylinder Scania D12 truck sized diesel engine modified for optical access using a Bowditch design. Engine specifications are given in Table 1. Only one cylinder was operational while the five others were motored. The engine was operated at a speed of 1200 rpm. The inlet air was conditioned in terms of pressure and temperature by an independent two-stage screw-compressor and an electrical heater. The inlet oxygen concentration was lowered below 5% by leading the exhaust gases from an external diesel furnace to the inlet of the optical engine, producing non-reacting jets. As reacting jets would produce a range of fluorescing species interfering with the fuel signal, using non-reacting jets was necessary to quantitatively determining the mixing.

Two different injector configurations were used to study the effect of inter-jet spacing on mixing in the recirculation zones. One symmetrical and one asymmetrical nozzle were used, both with four holes. Figure 1 shows schematics of the fuel jets. The resulting inter-jet angles were 45°, 90° and 135°. The latter was not investigated in this study.

Apart from inter-jet angle, the effect of injection pressure was also studied. Injection commands were adjusted to ensure identical start and end of injection for the different injection pressures. These parameters were confirmed using scattered laser light on the liquid fuel at the nozzle exit. Inlet temperature was set at 398 K in order to ensure complete

vaporization of the fuel when port-injection was used for calibration purposes, as explained below. The main operating conditions are summarized in Table 2. A diesel furnace working at stoichiometric conditions provided external exhaust-gas recirculation.

Table 1. Engine characteristics

Engine Specifications	
Engine type	Scania D12
Cycle	4-stroke
Number of cylinders	1
Number of intake valves	2
Number of exhaust	2
Bore [mm]	127
Stroke [mm]	154
Displacement [dm ³]	1.95
Compression ratio	15.1:1
Swirl number	2.18
Injector	
Type	Cummins common-rail
Number of holes	4
Orifice diameter [μm]	100
Inter-jet angles [°]	45 and 90

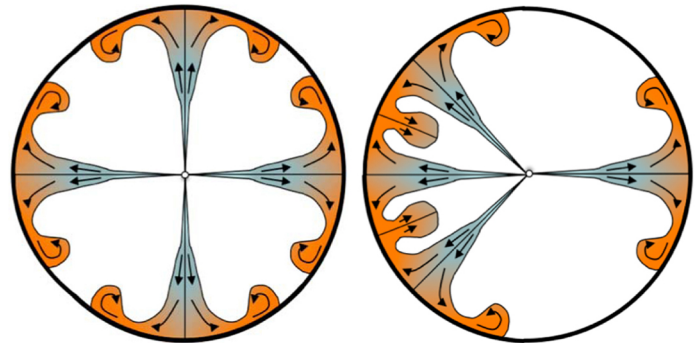


Figure 1. Schematic of the symmetrical (left) and asymmetrical (right) nozzle configurations. In each case, the nine o'clock jet was investigated.

Table 2. Operating conditions

Operating conditions	
Engine speed	1200 rpm
Inlet temperature	398 K
Inlet pressure	1.6 bar (a)
Inlet O ₂	< 5%
Actual start of injection	-7.5 CAD ATDC
Actual end of Injection	7.7 CAD ATDC
Injection pressure	1500-2000-2500 bar
Fuel	90% iso-octane/10% acetone
Estimated TDC temp.	896 K
Estimated TDC density	21 kg/m ³



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Fuel-Tracer Planar Laser Induced Fluorescence

Planar LIF is a common method to measure the fuel distribution in a combustion engine. Most commercial fuels contain several species that naturally fluoresce upon UV excitation and that can be used for LIF measurements [12]. However, when several species with different transport, evaporation, quenching and fluorescence properties fluoresce at the same time, quantification of the fluorescence intensities in order to get local equivalence ratios is extremely difficult. LIF measurements of commercial fuels are thus most often limited to qualitative measurements.

Therefore, fuel tracer LIF, where a fluorescent tracer is added to a non-fluorescing base fuel, is usually employed for quantitative measurements. This allows control of the tracer concentration, and simplifies the pressure and temperature dependencies of the signal. A comprehensive summary of quantitative fuel tracer-LIF in practical combustion systems can be found in [13].

Acetone was selected as fuel tracer in the present study due to its low pressure dependency on the combined absorption cross-section and fluorescence quantum yield [12]. The injection event was triggered around top-dead center (TDC) in order to further reduce pressure and volume variations during the measurements since piston displacement is limited around TDC. Furthermore, acetone is not prone to pyrolysis at temperatures below 1000 K [14]. The experimental conditions in this setup fulfill this criterion. Furthermore, the low intake oxygen mole fraction of the charge was used together with iso-octane as fuel to ensure non-reacting conditions and to avoid oxygen quenching of the acetone LIF signal.

Only a brief overview of the optical measurement techniques employed will be given in this section. Details about the laser-diagnostic aspects of the present investigation are presented in [11].

In order to relate the fluorescence signal intensity to fuel-air ratios, calibration measurements were conducted using port-injected fuel (90% iso-octane/10% acetone). Corrections for ambient pressure and temperature as well as laser fluence variations were made account to ensure the fidelity of the quantitative measurements.

Structured Laser Illumination Planar Imaging (SLIPI)

Quantitative fuel-tracer LIF measurements are difficult to perform in combustion engines. One important issue concerns the subtraction of background that is due to light scattered around the combustion chamber. Scattered laser light gives rise to secondary fluorescence from walls and regions outside the laser sheet, which is not easily subtracted as it overlaps spectrally with the signal. Detection of this secondary fluorescence will lead to inaccuracy in the measurements.

By using Structured Laser Illumination Planar Imaging (SLIPI) it is possible to remove these scattered light effects. SLIPI is based on laser sheets that are spatially modulated with a sinusoidal pattern, $E_{\text{laser}} = E_0 (1 + \sin(\omega x + p))$. The detected signal, I_1 , from one laser sheet is then

$$I_1 = I_B + I_S[1 + \sin(\omega x + p_1)] \quad (1)$$

where I_S is the amplitude of the modulation and I_B is the background offset arising from e.g. scattering and reflections. Figure 2 shows an example of a raw data image with a modulated laser sheet in homogeneous conditions (port fuel injection).

Combining three measurements with different phases, i.e. $p = 0^\circ, 120^\circ, 240^\circ$, it is possible to reconstruct how the image would look without the modulation. More significant, however, is that I_S can also be retrieved from these three measurements according to Eq. 2 [11]. SLIPI can thus suppress the background I_B from the images and reveal the signal originating from the laser sheet without any background due to scattered or reflected light.

$$I_S = \frac{\sqrt{2}}{3} \sqrt{[(I_1 - I_2)^2 + (I_1 - I_3)^2 + (I_2 - I_3)^2]} \quad (2)$$

The condition of the phases being $0^\circ, 120^\circ$ and 240° is essential for a correct image reconstruction using Eq. 2. However, in the case of measurements in engines, vibrations can be transmitted to the optical setup and slightly alter the phases. In these cases, Eq. 3 can be used since it is able to account for erroneous phase shifts. This equation was used in the present study due to identified phase shifts in the collected data. Further details regarding the SLIPI technique can be found in [10, 15].

$$I_S = \frac{1}{2|\sin(\frac{p_1 - p_3}{2})|} \left| (I_3 - I_1) + i \left\{ \frac{I_1 - I_2}{\tan(\frac{p_1 - p_2}{2})} - \frac{I_2 - I_3}{\tan(\frac{p_2 - p_3}{2})} \right\} \right| \quad (3)$$

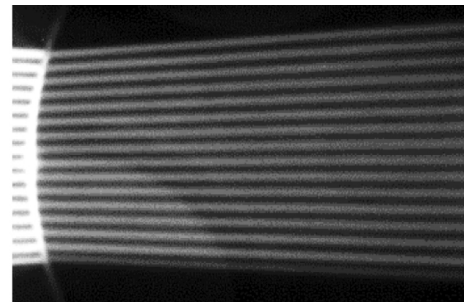


Figure 2. LIF image of a homogeneous case with port fuel injection using a modulated laser sheet, the signal was collected from below. The laser sheet enters the piston bowl from the left side through the quartz piston crown that can be seen as a stronger signal.