

Study of the Early Flame Development in a Spark-Ignited Lean Burn Four-Stroke Large Bore Gas Engine by Fuel Tracer PLIF

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ABSTRACT

In this work the pre- to main chamber ignition process is studied in a Wärtsilä 34SG spark-ignited lean burn four-stroke large bore optical engine (bore 340 mm) operating on natural gas. Unburnt and burnt gas regions in planar cross-sections of the combustion chamber are identified by means of planar laser induced fluorescence (PLIF) from acetone seeded to the fuel. The emerging jets from the pre-chamber, the ignition process and early flame propagation are studied. Measurements reveal the presence of a significant temporal delay between the occurrence of a pressure difference across the pre-chamber holes and the appearance of hot burnt/burning gases at the nozzle exit. Variations in the delay affect the combustion timing and duration. The combustion rate in the pre-chamber does not influence the jet propagation speed, although it still has an effect on the overall combustion duration. PLIF images also show that there is mainly lean unburnt gas, originating from the main-chamber, that exit the pre-chamber in the initial phase of ignition, indicating incomplete mixing of the gases in the pre-chamber prior ignition. These findings are also supported by CFD modeling performed on the Wärtsilä 34SG combustion system. Similar to the air entrainment in a diesel spray, the jets exiting the pre-chamber causes pronounced entrainment of compressed fresh charges into the burning jets, thus promoting heat transfer and subsequent ignition.

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INTRODUCTION

With low emissions in terms of NO_x , soot, CO_2 and sulphur, the large bore lean burn gas engine has become a viable alternative for many different applications during the last years. In addition to the most common application as a land based power plant alternative to gas turbines, both ship propulsion and locomotive traction are fast growing applications for these engines. The lower cost of natural gas relative to low sulfur diesel further enhances the value of gas engines in regions where the sulfur content is regulated. Due to the homogeneous lean air fuel mixtures required to suppress knock and NO_x formation, a conventional spark plug approach is not sufficient to achieve a steady ignition. One alternative, that is commercially available, is to run a conventional diesel process by injecting gas at high pressures [1,2]. A more common approach is, however, to employ a lean bulk charge that is ignited by a second more energetic ignition source. This ignition source could be the flame from a low volume pilot injection of diesel/fuel oil [3], or it could be a richer gas mixture trapped in a pre-chamber [4], which is the main focus of this

study. In this case, the richer charge in the pre-chamber is ignited by a spark plug. Pressure builds up as the combustion progresses and the ignited mixture is eventually pushed out through holes in the pre-chamber into the main chamber where it ignites the lean bulk gas. Even though the concept is conceptually understood, the actual ignition process is not well studied, neither in the pre- nor in the main-chamber, and more knowledge is required for the validation of computational models and to enable efficient optimization of the process. This paper focuses on the ignition process in the main-chamber.

To the author's knowledge, this is the first time PLIF is recorded from such a large bore gas engine. Thus, the challenges; in terms of achieving optical access, proper seeding, and compensating for optical aberrations that are associated with laser based optical measurement in large combustion chambers; are also addressed.

METHOD

Imaging System

To study the pre-chamber gas and flame propagation through the main chamber, PLIF from acetone seeded to the fuel was recorded [5]. The reason for probing acetone is that natural gas does not show any fluorescence when being excited in the UV/visible spectral region. Hence a fluorescent fuel tracer is needed. The first use of acetone as a fuel tracer in engine experiments was reported by Neij et al. [6]. Although acetone might not be an ideal tracer species, it is nowadays commonly used for this purpose in engine experiments. Its fluorescence properties under in-cylinder conditions have been thoroughly studied. Depending on the excitation wavelength, the yield can increase or decrease with increasing temperature. In the reported experiments where excitation was performed at 266 nm, the sensitivity to temperature variations is moderate [7, 8, 9]. The pressure dependence on the LIF signal was investigated by Grossmann et al. [8]. This study reveals that the fluorescence intensity from acetone in an air environment at low pressures, i.e. up to a few bar, increases slightly with pressure. At higher pressures, relevant to in-cylinder conditions, the influence from the pressure levels out. Further work by Yuen et al. [10] and Thurber et al. [7] revealed similar trends. A general requirement for a fuel tracer is that it follows the fuel in the charge preparation process and that it is burnt simultaneously with the fuel during combustion. A possible issue could be if the tracer suffered from pyrolysis prior to the base fuel during the compression stroke. However, experiments performed by Yip et al. [11] revealed no significant pyrolysis of acetone below 1000 K on the time scales that are relevant for engine measurements. The ability of acetone to follow natural gas, which is mainly methane, during the charge preparation, can be argued. In this study the acetone was introduced well upstream of the fuel nozzle. In addition, a mixing tank was added to the system to further ensure proper mixing of tracer and fuel prior to injection. Although the diffusion properties vary between fuel and tracer, this can be disregarded in this port-injected gas engine, where the fuel/air mixture can be considered as homogeneous at the time of ignition. The latter was also verified by recording fuel PLIF images late in the compression stroke.

As an excitation source the frequency quadrupled output from a pulsed Nd:YAG laser (Continuum Powerlite DLS 9010) is used. The repetition rate of the laser system was governed by the engine and ended up at 6.25 Hz in order to match the combustion frequency of the engine running at 750 rpm. The ~6 ns long laser pulses were formed into 40 mm high vertically oriented laser sheets using standard sheet forming optics and directed through the center of one of the liner windows (see Fig.1). Inside the cylinder the pulse energy is around 50 mJ/pulse. To prevent the engine induced vibrations from causing damage or misalignment to the optical components, the laser is placed on a pneumatically suspended and hydraulically dampened optical table.

The seeding system consists of a fuel injector injecting acetone in a 30 liter mixing tank located about 4.3 m upstream of the intake valve. The mixing tank and downstream fuel pipes are heated to prevent acetone condensation on the surfaces. The acetone (8 % per mass fraction fuel) is either only supplied to the pre-chamber fuel line or to both main- and pre-chamber fuel lines.

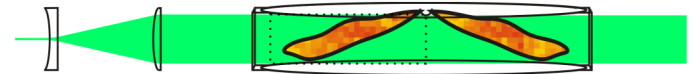


Figure 1. Schematic of the experimental setup. The dotted line represent the field of view.

The acetone fluorescence is imaged through a UV B. Halle 100 mm f/2 objective mounted with a Scheimpflug (tilt) adapter on an image intensified CCD camera (Princeton PI-MAX3). The camera is placed at an angle to the liner window, according to Fig.2, to image one of the pre-chamber jets. The curved inner surface of the liner window extends the field of view from ~70 % to ~95 % of the distance from the pre-chamber to the cylinder wall. The drawback with using a curved window is that, in addition to increase the field of view, the window also induces a focal shift and an inhomogeneous demagnification in the horizontal dimension. The Scheimpflug adapter aligns the image plane along the laser sheet. The optical pathway is simulated, using a homemade ray-tracing program, to find the optimal focal distance (in this case $f = 3200$ mm) of the positive cylindrical lens that is inserted in front of the camera lens to compensate for the focal shift. From the inset in Fig.2, it is obvious that the vertical lines completely vanish when imaging without the correction optics.

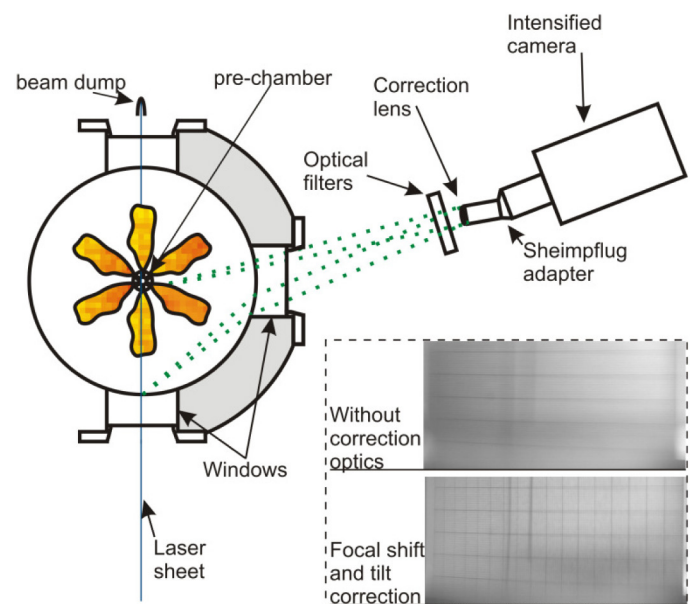


Figure 2. Image on the setup and description of the correction optics. In the insert images of a graph paper with and without correction optics are shown.

Engine Configuration and Operation Conditions

The experiments were performed on a single cylinder test engine with a combustion system from the Wärtsilä 34SG engine (SG-Spark Gas). The engine specification can be found in Table 1. The Wärtsilä 34SG engine is a port fuel injected lean burn gas engine with a spark plug ignited pre chamber. The lean mixture in the main chamber, with a lambda of about 2, is ignited by the separately fueled pre chamber with a close to stoichiometric mixture. The working principle is visualized in Figure 3. The engine model is turbocharged with cooled air, and is typically operated continuously at its nominal output.

Table 1. Engine specification of the Wärtsilä 34SG.

Engine type	4-stroke trunk piston
Cylinder bore	340 mm
Cylinder stroke	430 mm
Displacement	39.0 dm ³ / cylinder
Compression ratio	11.6:1
Number of valves	2 intake, 2 exhaust
Working process	Pre-mixed lean burn
Main fuel system	Port gas admission
Ignition system	Spark ignited pre chamber with separate fuel supply
Engine speed	750 rpm
Nominal output	500 kW/cylinder
Nominal BMEP	2.20 MPa (22.0 bar)
Cyl. configurations	9L, 16V, 20V

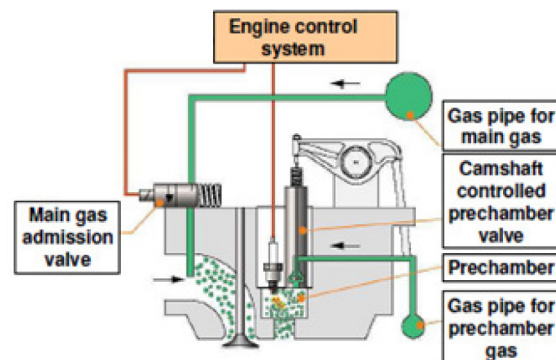


Figure 3. The working principle of the Wärtsilä 34SG spark ignited lean burn gas engine.

The fuel used for this study was Russian natural gas transported as LNG with specifications given in Table 2.

During the optical investigations the single cylinder engine was operated in skip firing mode, with skip firing sequences consisting of 140 consecutive combustion cycles followed by 160 motored cycles (without combustion). The purpose of motoring the engine is to control window surface temperature in order to minimize the risk of window failure due to thermal stress. To avoid influences by thermal transients, only the last 50 of the 140 consecutive combustion cycles were analyzed in terms of cylinder pressure and optical diagnostics.

Table 2. Composition of the natural gas.

Compound	Chemical Formula	Volume [mol%]
Methane	CH ₄	98.17
Ethane	C ₂ H ₆	0.83
Propane	C ₃ H ₈	0.11
i-butane	C ₄ H ₁₀	0.02
Nitrogen	N ₂	0.83
Methane number		95.3
Density [kg/m ³]		0.73
H/C-ratio [molar]		3.98
Low Heating Value [MJ/kg]		49.35

The operating point applied during the measurements has a NO_x emission level of 500 mg/Nm³ at 15% O₂, corresponding to about 2g/kWh. The selected NO_x level comes from the often referred German TA-luft air pollutant regulation. The engine load in the tests was 15.5 bar IMEP, which correspond to about 70% of the nominal load in the Wärtsilä 34SG engine. The operating conditions are shown in Table 3.

Table 3. Operation condition.

Name	TA Luft
Ignition timing	14° CA BTDC
Charge air pressure	2.17 bar
Charge air temperature	50° C
IMEP	15.5 bar
NO _x at 5 % O ₂ dry	506 mg/ Nm ³
Lambda	2.01
Exhaust gas temperature	482.47° C
Exhaust gas pressure	0.03 bar
Main chamber gas flow	17.31 g/s
Pre-chamber gas flow	0.29 g/s

Data Post Processing

To enable adequate data analysis some data post processing is performed. The rate of apparent heat release in the main and pre-chamber is extracted from the recorded pressure data and the positions of the flame fronts are evaluated from the images. Cylinder and pre chamber pressures versus crank angle are measured separately with two different pressure sensors. Only about 2 % of the total heat is released in the pre-chamber. Nevertheless, a separate heat release analysis is performed for the pre-chamber combustion with the purpose to investigate the interaction between the chambers in more detail. The heat release analysis is taking into account the mass flow between the chambers but not the heat transfer to the walls. More details about the heat release analysis can be found in an earlier publication [12].