

Preliminary Investigation of Exhaust Pressure Waves in a Single Cylinder Diesel Engine and the Impacts on Aftertreatment Sprays

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ABSTRACT

The pressure wave actions were investigated in the exhaust system of a single cylinder diesel engine through both experimental and simulation methods. The characteristics of the exhaust pressure waves under different engine operating conditions, such as engine load and exhaust backpressure, were examined. The results showed that the strength of the exhaust pressure wave was affected by both the in-cylinder pressure and the exhaust backpressure in the exhaust system during the period when the exhaust valves were open. The exhaust gas flow velocity was also estimated by the one dimensional simulation tool AVL BOOST™. The results suggested that the velocity of the exhaust gas fluctuated during the engine cycle, and followed trends similar to the exhaust pressure wave. The transient gas flow velocity was high when there was a strong compression wave, and it was reduced when the pressure fluctuations in the exhaust manifold were small. A shock tube test bench was set up to complement the empirical work performed on the engine system. Optical methods were used to study the effect of the pressure wave and the accompanying high velocity gas flow on the atomization and distribution of liquid sprays from a low pressure fuel injector. Such an injector is typically used in a diesel exhaust after-treatment system. From the results, it was seen that a transient high velocity gas flow had significant impacts on the spray development.

CITATION: Yang, Z., Dev, S., Jeftic, M., Aversa, C. et al., "Preliminary Investigation of Exhaust Pressure Waves in a Single Cylinder Diesel Engine and the Impacts on Aftertreatment Sprays," *SAE Int. J. Engines* 10(2):2017, doi:10.4271/2017-01-0616.

INTRODUCTION

Pressure wave actions are commonly encountered in reciprocating internal combustion engines due to the periodic gas exchange process. The pressure wave has been an interesting research topic because of its important impacts on engine performance. Firstly, the engine volumetric efficiency and gas exchange process are affected by pressure waves. Engine efficiency can be improved by properly designing the intake and exhaust system [1,2]. Moreover, the pressure wave induced non-uniform gas flow changes the gas composition of the in-cylinder charge, which can further influence the in-cylinder combustion process and engine-out emissions. In addition, the operation of turbine in turbocharged engines can be affected by the pressure wave action as well [3]. Due to these impacts, the pressure wave is an important consideration in engine control model development [4, 5, 6]. Previous studies on engine pressure waves include both experimental and simulation research work [7, 8, 9, 10]. The experimental method usually involves measurement of the pressure in the intake or exhaust manifolds under various engine operating conditions [8,9]. For pressure wave simulation, many researchers have used the one dimensional (1-D) approximation [7,10]. Since the pressure wave in the engine system primarily changes along the axial direction of the pipe, while the differences in the cross-sectional area have a minor effect, reasonable results have been obtained using the 1-D simulation methods [7,8].

In addition to the above mentioned impacts of pressure waves, there are some other situations where the pressure wave plays an important role. In modern internal combustion engines, sophisticated exhaust after-treatment systems are often used to reduce engine out emissions. These after-treatment systems include the three-way catalyst (TWC) in gasoline engines, selective catalytic reduction (SCR) and diesel particulate filter (DPF) in diesel engines. The distribution of the exhaust gas flow upstream of the aftertreatment converters can affect the active volume and subsequently the conversion efficiency of the converters [11, 12, 13]. Moreover, for the SCR and the DPF in diesel engines, a secondary injector is often used to provide a supplemental liquid such as urea or diesel fuel for emission reduction and catalyst regeneration. Oh et al. [14] investigated the spray distribution of an SCR injector and found that improved uniformity and atomization of the urea spray resulted in a higher NO_x reduction efficiency of the SCR. In their experiments, the gas flow was assumed steady. However, the actual exhaust flow can be highly pulsating with a high amplitude of transient velocity and pressure waves. Nishiyama et al. [15] used Endoscopic Stereo Particle Image Velocimetry (PIV) to measure the three dimensional exhaust gas flow around an oxygen sensor mounted on the exhaust manifold of a four cylinder gasoline engine. Their results showed that an exhaust flow with transient velocity greater than 60 m/s was produced after the exhaust valve opened. Under such flow conditions, the after-treatment spray could be affected which may further influence the function of a catalytic converter.

There were several reports on the interactions between exhaust flow and after-treatment sprays, and most of them were conducted on off-engine test benches using optical methods [14,16,17]. The gas temperature and mass flow rate were commonly investigated in these studies assuming steady gas flow conditions [14,16,17]. The main challenges for conducting after-treatment spray research directly on an engine system are the high temperature environment and the limited optical access, which can usually be complemented by the steady flow test benches. Yet, one of the deficiencies for a steady flow test bench is that it is difficult to replicate the pressure waves and pulsating flow conditions of an engine system. There are some other researchers using pulsating flow rigs [13,18] or shock tube devices [19, 20] to simulate the pulsating pressure and gas flow of an engine system. Liu [13] used a pulsating flow rig to study the effect of pulsating gas flow on the performance of a catalytic converter. Chalet et al. [15] developed a 1-D simulation model for calculating the flow at pipe junctions and verified the model with shock tube test results. The verified model was used later on to simulate the exhaust flow in an engine system and the results showed good agreement with the engine test results. These research results provided the background for investigating the after-treatment spray under unstable gas flow test conditions. From the authors' search, there is no comprehensive work on integrating pressure wave measurement on an engine, with off-engine spray research and 1-D computational simulation. This paper is a preliminary step in that direction with the primary objective being to understand the characteristics of the pressure wave under different engine operating conditions. A secondary objective is to study the effect of the pressure wave on the after-treatment injection process.

In this work, the exhaust pressure wave was measured and identified on a single cylinder compression ignition research engine under different engine operating conditions. The measurement results were also used to validate the simulation model based on the 1-D gas dynamic method using AVL BOOST™. The validated simulation model was then used to estimate the exhaust gas flow velocity. Thereafter, an off-engine shock tube test bench was used to create a simulated exhaust gas flow condition to investigate the impacts of the pressure wave and pulsating gas flow on the droplet breakup and spray distribution of an after-treatment injection using optical methods.

APPROACH

Experimental Setup

Engine Test Setup

The engine tests were conducted on a single cylinder research engine which was modified from a four cylinder production diesel engine. The specifications of this engine are listed in Table 1. The intake and exhaust system of the first cylinder were isolated from the other three cylinders which operated at a fixed low load condition to motor and balance the research cylinder during engine tests. The intake and exhaust conditions, as well as the injection pressure, injection timing and duration, of the research cylinder were independently controlled by in-house designed LabVIEW programs. The configuration of the engine test system is shown in Figure 1.

A critical parameter in this study was the exhaust pressure. The exhaust pressure measuring port was located on a straight exhaust pipe 10 cm downstream of the exhaust valve. The diameter of the pipe was 25.5 mm. Further downstream, a diesel oxidation catalyst (DOC) and an exhaust surge tank were installed in the exhaust system. The DOC was used to reduce incomplete combustion products while the surge tank was used to dampen the pressure wave action and provide a steady condition for the in-cylinder combustion research. These components, however, would not affect the pressure wave actions as the measuring port was right after the exhaust valve. The downstream conditions had relatively minor effects on the pressure wave and are outside the scope of this paper. A more comprehensive analysis is provided in [21].

A Kistler 4075A10 piezoresistive pressure transducer was used for the exhaust pressure measurement. The natural frequency of the transducer was 120 kHz. An AVL GU13P piezoelectric pressure transducer was used to measure the in-cylinder pressure. Both the in-cylinder and exhaust pressures were acquired at a sampling rate of 0.1 °CA and recorded on a Windows based computer. 200 consecutive cycles were recorded at each data point and the averaged value was reported. The engine speed was kept constant at 1500 rpm throughout the tests which resulted in an equivalent sampling frequency of around 90 kHz. A number of thermocouples were installed at different locations in the exhaust system to monitor the exhaust temperature which also provided information for boundary conditions in the simulations. The primary exhaust temperature measurement was performed using a K-type thermocouple which was installed about 5 cm downstream of the exhaust valve on the exhaust pipe. The exhaust temperatures mentioned in the subsequent sections were measured using this thermocouple.

Table 1. Test engine specification

Exhaust Valve Diameter	28 mm	Intake Valve Diameter	33.4 mm
Total Engine Displacement	1.998 Liters	Maximum Exhaust Valve Lift	8.64 mm
Bore	86 mm	Maximum Intake Valve Lift	12.5 mm
Stroke	86 mm	Intake Valve Opening (IVO)	687 °CA
Connecting Rod	144 mm	Exhaust Valve Opening (EVO)	491 °CA
Compression Ratio	18.2:1	Intake Valve Closing (IVC)	217 °CA
Valves per Cylinder	4	Exhaust Valve Closing (EVC)	10 °CA

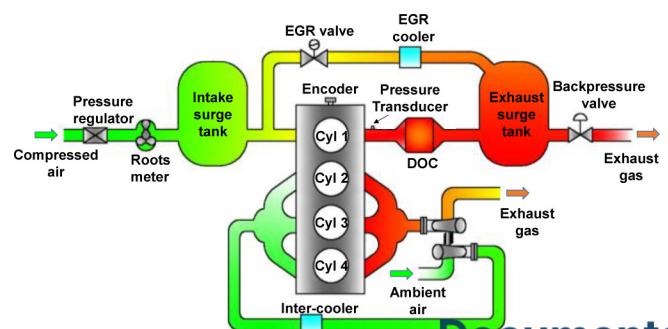


Figure 1. Engine test setup.

Shock Tube Test Setup

A shock tube device was used to create pulsating flow conditions which had a similar pressure and velocity to the engine exhaust manifold. The driver to driven section pressure ratio was controlled by using different types of diaphragms. The shock tube was closed at one end and open to the atmosphere at the other end. A liquid droplet (Figure 2) or a low pressure after-treatment injector (Figure 3) was mounted at the open end of the shock tube and the interactions between droplets, pressure wave and high velocity gas flow were investigated by optical methods. The total length of the shock tube was 1.36 m with a 1 m long driven section and 0.36 m long driver section. The inner diameter of the tube was 23.8 mm. Compressed air was used as charging gas in the tests. The compressed air was not heated, thus the impact of gas temperature was not investigated in this set of tests.

An SSI Technologies pressure transducer (model number: P51-200-S-A-136-5V-000-000) was mounted on the driver section 15 cm away from the diaphragm. This transducer was used to measure the charging pressure and record the diaphragm burst pressure. Two Kistler 4075A10 pressure transducers were mounted on the driven section of the shock tube. The first one was mounted 10 cm downstream of the diaphragm location and the second 10 cm before the open end. When the diaphragm burst, a shock wave was generated and transmitted downstream. The first Kistler pressure transducer detected the pressure rise and sent out a trigger signal to initiate data recording. The signals from all the pressure transducers were transmitted and recorded on a real-time controller (RT). A LabVIEW program was used to control the data recording process with a sampling frequency of 100 kHz. The pressure data from 20 ms before until 30 ms after the trigger were recorded

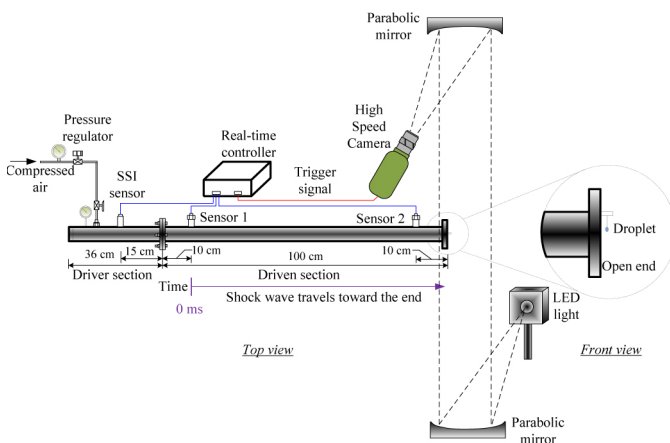


Figure 2. Shock tube test setup with a single droplet

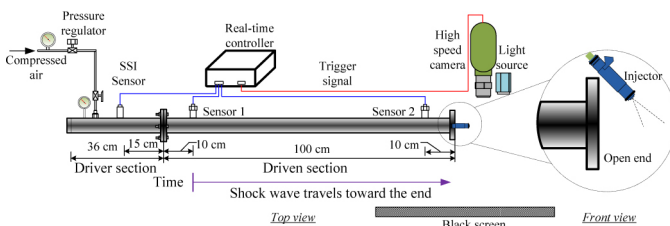


Figure 3. Shock tube test setup with a low pressure injector

A Vision Research Phantom v7.3 high-speed camera was used to record the breakup process of liquid droplets under pulsating gas flow. Shadow graph images were taken to record the detailed interactions between the gas flow, the pressure wave and a single droplet, while direct images were recorded to show the behavior of a liquid spray under pulsating gas flow conditions. The camera speed was set to 40000 fps with a resolution of 512×128 pixels and an exposure time of $8 \mu\text{s}$ for the shadow graph images. For the direct image of the injection tests, the camera speed was set to 20000 fps with a resolution of 256×512 pixels and an exposure time of $47 \mu\text{s}$. All the droplet and spray images were acquired at room temperature. The camera was triggered by the same pressure trigger that was used for data recording. The reference time zero was thus from the time when the shock wave arrived at 10 cm downstream of the diaphragm in the driven section.

Simulation Method

Although the transient exhaust pressure could be measured with the fast response pressure transducer, the transient exhaust gas flow velocity was difficult to measure directly. This information was attained through the simulation method based on the measured pressure and temperature information.

The AVL BOOST™ software is a 1-D simulation tool often used for engine simulations. This software features models for different components in the engine system, such as cylinder, pipe, plenum and catalytic converter. Three dimensional effects, such as frictional loss at pipe elbows, were simulated by flow coefficients. The simulation boundary conditions, such as pressure and temperature, were set to the same values as in the engine tests. The in-cylinder pressure acquired from engine tests was used as an input boundary condition for the pressure wave simulation.

The pipe flow simulation in AVL BOOST™ is based on the Euler equations. An essentially non-oscillatory (ENO) shock capturing scheme is used to solve the non-linear governing equations. The scheme is based on a finite volume approach where the value at the end of the time step is calculated based on the value at the beginning of the time step and the flux through the cells' borders. The mass, momentum, and energy flux are calculated through the conservation equations [22]. The ENO schemes use adaptive stencils to automatically achieve high order accuracy [22].

RESULTS

Engine Exhaust Pressure Wave and Gas Flow Velocity

Engine Test Results

The exhaust pressure was directly measured during engine tests. With the single cylinder setup, the interactions between different cylinders were avoided. The phase of the exhaust pressure wave with respect to the piston and the valve movement was clearly visualized over a complete cycle of 0° to 720° crank angle (CA), as shown in Figure 4. The first phase was during the intake stroke where the exhaust valves closed (EVC) at 10°CA , shortly after the intake TDC (at 0°CA). Then the intake valves closed (IVC) at 217°CA . Thereafter, both the intake