

Direct Injection of Diesel-Butane Blends in a Heavy Duty Engine

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ABSTRACT

Increasing fuel prices keep bringing attention to alternative, cheaper fuels. Liquefied Petroleum Gas (LPG) has been well known for decades as an alternative fuel for spark ignition (SI) passenger cars. More recently, aftermarket LPG systems were also introduced to Heavy Duty transport vehicles. These (port fuel) systems either vaporize the liquid fuel and then mix it with intake air, or inject fuel into the engine's intake ports.

While this concept offers significant fuel cost reductions, for aftermarket certification and large-scale OEM use some concerns are present. Unburned hydrocarbons (UHC) and carbon monoxide (CO) emissions are known to be high because of premixed charge getting trapped into crevices and possibly being blown through during valve-overlap. Apart from the higher emission levels, this also limits fuel efficiency and therefore cost savings.

Direct injection of LPG offers a solution to the aforementioned concerns by directing the fuel to the desired areas of the combustion chamber. To investigate the potential of this concept, diesel has been blended with liquid butane, in different ratios. These blends were directly injected into a heavy duty test engine, using a standard common rail injector.

Results show that even at low loads, a butane mass fraction of one-third can be used without negatively affecting emissions. For direct injected butane, hydrocarbon emissions were found to be an order of magnitude lower than when port fuel injected butane is used. At this butane fraction, smoke

emissions decrease by 50%. Because a high combustion efficiency is retained, fuel cost savings can be significant. At higher loads, an even higher butane mass fraction can be used, further enhancing the fuel cost saving potential.

INTRODUCTION

Due to increasingly stringent emission standards, engine development is forced to invest heavily in research for advanced combustion and exhaust aftertreatment systems. The exotic materials used in aftertreatment are boosting production costs; therefore reduction of in-cylinder emission formation is needed. Furthermore, rising fuel cost and a focus on reduction of greenhouse gases drive developments towards a better efficiency of the internal combustion engine.

LPG (Liquefied Petroleum Gas) has for long been used as an automotive fuel in light vehicles like private cars and taxis. LPG is a waste product of the refining process of fossil fuels, resulting in a low fuel price [1]. LPG consists of butane and propane, and depending on fuel grade and region around the world, LPG ranges from nearly pure propane (95%) to nearly all butane (>80 %). In the Netherlands, LPG is widely available and due to tax benefits it is attractively priced compared to, for example, diesel.

Recently, LPG supply systems in diesel engines have attracted considerable attention due to the requirement of more powerful engines in, for example, urban buses [2]. LPG can be used in heavy-duty diesel engines combining port fuel injection of LPG and a direct injection of diesel. Dual fuel engines equipped with a port fuel injection (PFI) system typically suffer from the problems of poor brake thermal efficiency and high HC emissions, particularly at low loads

[2]. According to Poonia et al [3], HC emissions can be lowered and brake thermal efficiency can be increased using hot Exhaust Gas Recirculation (EGR), resulting in a higher intake temperature.

All of the aforementioned investigations concluded that using port fuel injection of LPG, operational costs savings are possible. However, these savings were shown to come with a significant emissions penalty. A possible workaround to the latter problem could be the combustion of a premixed blend. The goal of this research is to explore whether the use of a premixed fuel can neutralize the emission penalty of PFI LPG, while maintaining the operational cost savings. This might be extended to an operational costs saving combined with a simultaneous emission benefit.

Therefore, in this investigation a premixed butane-diesel blend is directly injected, using only one fuel system, to determine the influence of butane on conventional diesel combustion. For hardware safety reasons a diesel-butane blend is used, rather than a diesel-LPG blend. When using real LPG, the propane in the blend would lead to a higher vapor pressure, which is more hard to control on the experimental set-up and therefore would present the risk of over pressure in the injector's fuel supply line.

Using a dual fuel PFI system, Jian et al [2] found a significant reduction in soot emissions, but an increase in HC, NO_x and CO emissions for the same power output. Donghui et al [1] used a premixed LPG/diesel blend for a directly injected diesel engine and found longer ignition delays. This resulted in a better premixing of the fuel with air, a reduction in soot emissions, a small increase in HC emissions and slightly higher fuel consumption. As a reason for lower soot production with DI premixed blends, Cao and coworkers [4] suggest better premixing of the fuel with air due to flash boiling in the injected spray when LPG is added.

The key issue for the direct injection strategy of premixed blends is finding the right diesel-butane content at different operating conditions. A low butane content may slightly reduce costs but have no effect on soot emissions. Higher butane content can further reduce costs and emissions; however in-cylinder pressure can increase rapidly and damage the engine [1]. When engine load is low, higher butane content can influence combustion phasing, performance and emissions.

Apart from the changing combustion phasing and emissions, the change in fuel consumption plays an important role. A diesel-butane blend contains less energy per volume, resulting in higher fuel consumption in terms of L/km [1,4]. With the right amount of butane in the blend this fuel penalty might be compensated by lower fuel costs.

EXPERIMENTS

EXPERIMENTAL APPARATUS

Over the last years, at Eindhoven University of Technology a versatile test engine setup, referred to as CYCLOPS, was developed for testing of fuels, engine hardware and combustion concepts. This engine set-up is described in detail by Leermakers et al. [5] and summarized below, with the changes made for the current investigation.

The CYCLOPS is a dedicated engine test rig, see Table 1, based on a DAF XE 355 C engine. Cylinders 4 through 6 of this inline 6 cylinder HDDI engine operate under the stock DAF engine control unit and together with a water-cooled, eddy-current Schenck W450 dynamometer they are merely used to control the crankshaft rotational speed of the test cylinder, i.e. cylinder 1. Apart from the mutual cam- and crankshaft and the lubrication and coolant circuits, this test cylinder operates autonomously from the propelling cylinders. Standalone air, EGR and fuel circuits have been designed for maximum flexibility, as is discussed below.

Table 1. Cyclops test setup specifications

Base Engine	6 cylinder HDDI diesel
Cylinders	1 Test cylinder
Bore [mm]	130
Stroke [mm]	158
Compression ratio	14.9 (original 17.0)

Fed by an air compressor, the intake air pressure of the test cylinder can be boosted up to 5 bar. Non-firing cylinders 2 and 3 function as EGR pump cylinders, see Figure 1, the purpose of which is to generate adequate EGR flow, even at 5 bar charge pressure and recirculation levels in excess of 70%. The EGR flow can be cooled both up- and downstream of the pump cylinders. Surge tanks, to dampen oscillations and ensure adequate mixing of fresh air and EGR, and pressure relief valves, to guard for excessive pressure in the circuit, were also included in the design. Please note that in this investigation no EGR is used.

For measuring gaseous exhaust emissions, a Horiba Mexa 7100 DEGR emission measurement system is used. Exhaust smoke levels are measured using an AVL 415 smoke-meter. All quasi steady-state engine data, together with air and fuel flows and emission levels are recorded by means of an in-house data acquisition system (TUEdACS). A SMETEC Combi data acquisition system is used to record and process crank angle resolved data.

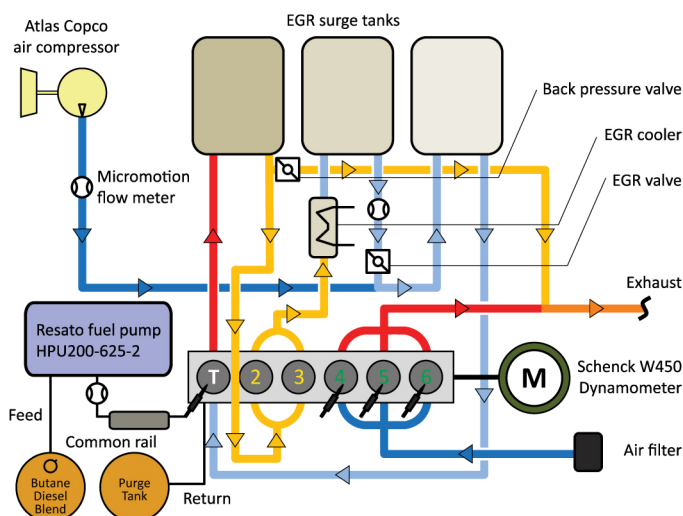


Figure 1. Schematic of experimental setup CYCLOPS: modified DAF engine using separate fuel, air and EGR systems for one dedicated test cylinder

For the present measurements, the fuel system was adjusted to inject pre-mixed diesel-butane blends directly into cylinder 1. A standard LPG tank with a built-in low pressure fuel pump provides the blend at 5 bar over the vapor pressure to the high pressure pump. Fuel density is monitored to be confident that the fuel blends do not partially or fully separate within the fuel system. This double-acting air-driven Resato HPU200-625-2 pump can deliver a fuel pressure up to 4200 bar, but for the present investigation the fuel pressure is set to 1500 bar. An accumulator is placed near (~ 0.2 m) the fuel injector to mimic the volume of a typical common rail and dampen pressure fluctuations originating from the pump. The prototype common rail injector used has a nozzle with 8 holes of 0.151 mm diameter and a cone angle of 153 degrees. The injector leak flow is captured in a surge tank. This tank will reach a pressure of 10 bar maximum, because this is the highest vapor pressure of the blends at 90°C, which is the temperature of the cylinder head at the leak flow of the injector.

To test direct injection back to back with port fuel injected butane, the setup is also equipped with a port fuel injection (PFI) system. In this case, the low pressure pump in the LPG tank is directly coupled to this liquid fuel PFI injector.

FUELS AND OPERATING CONDITIONS

To test the viability of direct injection of a diesel mixed with LPG, a standard EN590 diesel fuel is compared to three butane-diesel blends. These blends are called But14, But33, But50, after their respective mass percentages of butane in the blend. Butane is used instead of LPG, both to be certain of the blend composition and to limit blend vapor pressures for hardware safety reasons. Injector stability is guaranteed

up to 10 bar back pressure, therefore the return pressure should not exceed this value. The blends have been chosen accordingly.

To calculate blend properties, data from Younglove [6] and the DIPPR database [7] are used. Kalghatgi has given a relation in [8] to calculate the estimated Cetane number, based on the octane number of a low reactive fuel, such as LPG. Furthermore, Kalghatgi states that the Cetane number scales linearly with the molar fractions of the two fuels in the blend. The more butane is added to the fuel the less reactive the blend becomes. Note that the energy density per unit volume also decreases when the butane content is increased.

The maximum vapor pressure of the blends in the fuel line is calculated using Raoult's law [9], which states that the vapor pressure of an ideal solution equals the sum of the vapor pressures of each chemical component times its mole fraction in the liquid phase. In this case the vapor pressure of diesel can be neglected.

Besides testing diesel and three diesel-butane blends, as a reference also port fuel injected pure butane is investigated, combined with direct injected diesel. In these cases, the same mass percentages of butane of the total injected fuel are used. In Table 2 all further properties of the blends, except for the estimated cetane number (ECN), are calculated on a mass fraction base, since the content of butane in the blend is given in mass fractions.

Table 2. Fuel properties of diesel-butane blends

	Diesel	But14	But33	But50	Butane
wt% Butane	0	14	33	50	100
vol% Butane	0	20	43	60	100
LHV [MJ/kg]	43.00	43.39	43.92	44.38	45.75
LHV [MJ/L]	37.30	35.27	32.96	31.23	27.70
Density [kg/m ³]	830	790	757	690	550
ECN [-]	55.90	41.90	31.40	25.50	16.38
Psat [bar] (@ 365 K)	negl.	4.50	7.98	9.88	12.9

A load of 8 bar gross IMEP was selected for this test of premixed diesel-butane blends. This is approximately one third of rated power and is considered a reasonable approximation of average load. A second 12 bar IMEP load (ca. 50% of rated power) is also tested, to shortly check the behavior at higher loads. Loads are maintained constant by a longer actuation duration when more butane is added to the blend. In practice this can be realized by enlarging throttle pedal position, creating a longer actuation duration of the