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Research paper

Direct injection of gaseous LPG in a two-stroke SI engine for improved performance

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HIGHLIGHTS

- Energy saving, low pressure, direct gaseous LPG injection in engine.
- Significant reduction in HC emissions at all operating conditions.
- No significant changes in injection timings for different throttle positions.

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ABSTRACT

Improvements in a two-stroke, spark-ignition (2S–SI) engine can be realized by curtailing short-circuiting losses effectively through direct injection of the fuel. Liquefied petroleum gas (LPG) is an alternative transportation fuel that is used in several countries. However, limited information is available on LPG fuelled direct injected engines. Hence, there is a need to study these systems as applied to 2S–SI engines in order to bring out their potential benefits. A manifold injected 2S–SI engine is modified for direct injection of LPG, in gaseous form, from the cylinder head. This engine is evaluated for performance, emission and combustion. Evaluation at various throttle positions and constant speed showed that this system can significantly improve the thermal efficiency and lower the hydrocarbon (HC) emissions. Up to 93% reduction in HC emissions and improved combustion rates are observed compared to the conventional manifold injection system with LPG. CO emissions are higher and peak NO emissions are lower with this system due to the presence of richer in–cylinder trapped mixtures and charge stratification. This system can operate with similar injection timings at different throttle positions which make electronic control simpler. It can work with low injection pressures in the range of 4–5 bars. All these advantages are attractive for commercial viability of this engine.

1. Introduction

There are several applications for which two-stroke spark ignition (2S–SI) engines are the most suitable prime movers. Their high power to weight ratio, simple construction and low initial cost make them attractive power sources for small two and three wheeled vehicles. However, the high levels of unburned hydrocarbon (HC) emissions and poor fuel economy make them generally unacceptable for these applications. In these engines during some part of the cycle, both exhaust and intake ports remain open resulting in fuel or fuel-air mixture to directly escape through the exhaust ports. The short-circuiting of the fuel-air mixture during the scavenging process is the reason for high levels of HC emissions.

In several parts of Europe, USA and Asia two-stroke spark ignition engines are still widely used for compact applications and in small vehicles. Recently reported research innovations [1] on 2S–SI gasoline engines show the potential of low-pressure direct injection. Development of such systems for small two-stroke engines is relevant due to the increased cost and complexity of high pressure gasoline direct injection (GDI) systems.

Abbreviations: LPG, Liquefied petroleum gas; MI, Manifold injection; 2S–SI, Two-stroke spark-ignition engine; MBT, Minimum advance for best torque; DI, Direct injection; SOI, Start of injection; LPG_DI, Direct injection of gaseous LPG from cylinder head; IT, Injection timing; TP, Transfer port; BP, Boost port; EP, Exhaust port; HC, Hydrocarbon; NO, Nitric oxide; CO, Carbon monoxide; °CA, Degree Crank angle; BTE, Brake thermal efficiency; Φ, Equivalence ratio; GDI, Gasoline direct injection.

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In four-stroke SI engines, electronically controlled fuel injection, through the intake manifold, with stoichiometric operation, along with a three way catalytic converter can deliver significant emission benefits. However, such a method cannot provide significant emission benefits in a conventional two-stroke SI engine where the main problem is the loss of fuel during the scavenging process. Moreover, charge dilution in the two-stroke engine also poses difficulty in catalyst light-off. Thus only methods like injecting the fuel directly into the combustion chamber late in the intake process or even after the exhaust port closure can reduce or eliminate short-circuiting losses. Additionally, in the case of small two-stroke engines the methods that can be employed should be simple and cost effective. The challenge is in realising a cost effective system which can lead to preparation of the mixture in the short time that is available between introduction of the fuel and combustion. Gasoline direct injection (GDI) systems are very promising in terms of emissions and performance in a two-stroke engine because of their potential to reduce short-circuiting if the fuel is injected close to exhaust port closure.

Use of Liquefied petroleum Gas (LPG) in spark–ignition engine offers several benefits. The properties of LPG and gasoline are compared in Table 1. Higher octane number, flame velocity and wider flammability limits of LPG compared to gasoline results in greater resistance to knock and possibility of operation with very lean mixtures. Additionally, being attractive in terms of cost and availability of supply networks, LPG is widely used in three-wheelers for transportation in several Asian countries [2]. Most of these vehicles run on carburetted four-stroke SI engines. Gaseous LPG in carburetion or manifold injection generally results in reduced volumetric efficiency and power since the gas replaces some amount of intake air [2–5]. Recent work shows that careful control of LPG temperature is necessary in manifold injection to control loss in power and NO emissions [6]. Manifold injection or carburetion of LPG in 2S–SI engines have also been reported to emit higher levels of HC compared to their gasoline counterparts [2,7,8].

From the discussion above, it can be inferred that direct injection of gaseous LPG could offer several benefits in two-stroke SI engines. LPG being stored at moderate pressures of 7–8 bar (abs), use of a fuel pump can be avoided by suitably managing the timing of injection. This can provide a more cost-effective and energy saving solution as compared to GDI systems employing high pressure pumps.

1.1. Background

Mechanical injection of gasoline through the cylinder head [9], electronically controlled injection through the cylinder barrel [10] and injection through a swirl chamber on the cylinder barrel [11] have been effective in improving performance and emissions of small two-stroke SI engines. Air-assisted low pressure injection systems have also been explored in this context [12]. Several methods of air assisted direct injection of gasoline like the Orbital combustion process [12–14] and fully atomized stratified combustion process [15] could achieve about 80% reduction in HC emissions as compared to a premixed charge system. In another recent work with gasoline as the fuel, good improvement in brake thermal efficiency and about 38% reduction in HC emissions were obtained through air assisted direct cylinder barrel injection in a 2S–SI engine [16]. A direct mixture injection system, developed at IIT Madras, for a gasoline fuelled two-stroke SI engine, also reported 66% reduction in HC emissions and improved brake thermal efficiency [17]. Recently, it has also been reported that low pressure direct cylinder barrel injection of gasoline in a 2S–SI engine can achieve Euro 4 emission standards [1].

The investigations on direct injection of LPG in spark ignited engines is quite less, more so in the context of two-stroke engines. The semi-direct injection strategies like boost port injection of LPG [8] and air injection into transfer ducts in conjunction with LPG induction through intake manifold (AI-LPG-IND) [18] were successful in reducing HC emissions significantly. In the case of boost port injection of LPG, up to 19% reduction in HC emissions as compared to manifold injection, was reported. However, lower brake thermal efficiency and heat release rates were also reported in this work, at higher throttles, with fuel lean mixtures [8]. In the case of AI-LPG-IND system, up to 40% reduction in HC was obtained [18], however, with no benefit in thermal efficiency. This indicates that the reduction in HC emissions with improvement in efficiency can probably be obtained with direct injection alone.

In an earlier work, direct injection of LPG from the cylinder head of a 2S–SI engine, at idling conditions, showed significant reduction in HC and CO emissions over an LPG premixed system [19]. Reduction in HC was about 67%. Improvement in fuel economy of up to 17% was reported when a two-stroke, direct injection system on propane was run with near stoichiometric mixtures [20]. In this case, reduction in HC emissions was up to 88%. However, these experiments were conducted at a few selected conditions. In another work on direct injection of LPG, at 30% throttle and selected pulse widths of fuel injection, HC emissions could be reduced to 400 ppm [21]. Though late injection timings offer possibility of reduction in short circuiting, they led to misfiring particularly at lean mixtures. Higher HC emissions were also observed for late direct injection of compressed natural gas in a four-stroke SI engine [22]. Thus injection timing of the gas (LPG in the present paper) influences performance and emissions significantly with direct injection.

In summary, it can be seen that only limited work has been reported on direct injection of LPG in two-stroke SI engines [19–21]. These experimental results have mainly focussed on the effect of injection timing of LPG and the engine was run near stoichiometric conditions. The equivalence ratio for the best performance and emissions with direct injected LPG could be quite different from manifold injection of LPG. The results presented in the existing literature also spans over a limited range of operating conditions.

1.2. Present work

The objective of the present work is to develop a low pressure, gaseous LPG, direct injection system for a 2S–SI engine and to evaluate its performance, emissions and combustion. To facilitate this, a 2S–SI, carburetted, gasoline engine was modified to work with an injector mounted on its cylinder head through which LPG was injected in the gaseous form. The tests are done on a two-stroke three-wheeler engine in which LPG is widely used as a transportation fuel in India. Based on the conclusions of the literature survey in the last section, it is considered important in the present work to run a direct injected LPG, two-stroke engine at

Table 1
Fuel properties [19,27].

Property	Unit	Gasoline	LPG
Lower heating value	MJ/kg	44	45.7[a]
Stoichiometric A/F	mass basis	14.7	15.5
Motor octane number		80–90	90–97
Flame speed	cm/s	37.5	38.2
Density	kg/m^3	735	2.26 (gas)
Auto-ignition temperature	°C	371	405–450

[a] at 1atm. & 15 °C.