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Review article

Relationship between LPG fuel and gasoline injection duration for gasoline direct injection engines

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HIGHLIGHTS

- Concise description of gasoline and LPG fuel injection flow.
- Experimental method to compare gasoline and LPG fuel injectors flow characteristics.
- Applicative formula to control LPG fuel injector for gasoline direct injection engines.

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ABSTRACT

LPG, *liquified petroleum gas*, is one of the most popular alternative fuels for internal combustion engines. Currently, it is quite easy to adapt a gasoline Multipoint Injection (MPI) engine's fuel system to LPG supply. There are several types of systems that adapt the engine in this way, and many manufacturers, which provide different structural solutions. Usually the LPG control unit is based on signals from the original gasoline supply system. This method is more complicated for direct injection engines, where the fuel dose depends not only on the injection duration but also on variations in injection pressure. In this study the relationship between LPG fuel and gasoline injection duration for gasoline direct injection engines was investigated. This relationship took gasoline injection pressure as a variable. The analysis was based on simple equations of incompressible and compressible steady flow. It was improved by an experiment which allowed the evaluation of injectors' flow characteristics. The results were also compared with the data provided by the manufacturer of LPG systems for MPI engines.

Contents

1. Introduction

Internal combustion engines are one of the main power source of for various types of vehicles. Over the years engine construction has been improved, achieving higher power and reduced emissions of pollutants. The result of this process is high precision engine's control and a significant increase of overall efficiency and reduction of fuel consumption. The most common fuel for internal combustion engines is still made out of oil, but continuous increases in oil prices has increased interest in alternative fuels.

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Nomenclatures

Roman letters

c_p	specific heat at constant pressure (J/kg K)
f	frequency of the flow variability (Hz)
i_{cyl}	number of cylinders
L	characteristic dimension L (m)
m	mass (kg)
$\dot{m}$	mass flow (kg/s)
$\dot{m}_{stoich}$	stoichiometric cylinder mass air flow (kg/s)
M	stoichiometric air demand (kg/kg)
n	rotational engine speed (rev/s)
N	number of injection
t	injection duration (s)
K	coefficient
p	pressure (Pa)
R	gas constant (J/kg K)
Sh	Strouhal number
T	temperature (K)
T_0	intake air of temperature (K)
u	flow velocity (m/s)
V	volume (m^3)

Greek letters

λ	air excess coefficient
Δp	injection pressure (Pa)
μA	effective flow area (m^2)
ρ	density (kg/m^3)

Subscripts

AIR	air
BEN	gasoline
LPG	liquified petroleum gas

Liquefied petroleum gas (LPG) is an alternative fuel used on a large scale to replace gasoline. LPG is a by-product of natural gas production and crude oil refineries [1,2] and the higher H/C rate improves combustion process and reduces emission as compared to gasoline [3].

The first generation of solutions delivered fuel to the engine using a mixer mounted in the intake manifold. Adjusting the mixture composition was performed by vacuum at the throttle in a similar way to a carburettor [4]. This resulted in a lack of precision and unequal distribution of fuel to the cylinders. The next generation system was improved by introducing single-point fuel injection (SPI), equipped with an exhaust system with a lambda sensor [5,6]. A signal from the lambda sensor was used to control a step motor, which provided the right amount of LPG fuel. The accuracy of control increased but problems with the uniformity of fuel distribution still persists.

Strict international regulations led designers to introduce multi-point fuel injection (MPI), so-called "third-generation" systems. This led to a significant increase in the uniformity of fuel distribution [7,8], since each cylinder is fuelled by independent single injector. These systems perform a LPG-gas sequential multi-point intake port fuel injection managed by a "slave" ECU, which is controlled by the main gasoline ECU [9].

In a MPI engine gasoline pressure is constant and the amount of fuel delivered to the cylinder depends only on injection duration. When a LPG system is installed the opening durations of the petrol injectors t_{BEN} generated by the main petrol ECU are read by the LPG ECU. The opening duration of LPG injectors is obtained by simply multiplying the gasoline injection duration by a coefficient "K":

$$t_{LPG} = K \cdot t_{BEN} \tag{1}$$

The coefficient K is estimated in a calibration procedure, which is carried out directly after the installation of a new LPG system in a vehicle. To increase accuracy, the manufacturers of LPG systems divide the full t_{BEN} range into a few sections with different values of K usually in range between 0.6 and 1.8.

Installations that deliver LPG fuel to the intake system meet the operational and technical requirements for MPI and SPI engines, but there are difficulties with customising them to gasoline direct injection engines since the gasoline is delivered directly into the cylinder whereas the LPG fuel is delivered to the inlet port.

Fig. 1 shows that in the most popular VW gasoline direct injection engines – the naturally aspirated FSI and turbocharged TSI types – a few different modes of operation are observed. For naturally aspirated engines the following three modes could be distinguished:

- combustion of lean stratified mixture at low loads,
- combustion of lean homogeneous mixture at medium loads,
- combustion of homogeneous mixture at high loads.

An additional mode with combustion of lean homogeneous mixture and exhaust gas recirculation (EGR) could be observed for turbocharged engines at part load.

With each mode the fuel system of VW gasoline direct injection engines is controlled in different ways. By contrast to the multipoint system (MPI), the injection pressure Δp_{BEN} is not the same but varies from a few up to 120 bars. The beginning of injection by lean stratified combustion mode is shifted from intake to the end of the compression stroke. The intake valves are then closed and only gasoline fuelling is possible if a conventional LPG installation with injectors placed in inlet ports is applied. In gasoline direct injection engines equipped with a MPI LPG system with an injector in the inlet port (Fig. 2), fuel could not be switched manually or automatically from gasoline to LPG, but depends on the operation mode the engine has to operate on gasoline, on LPG or both gasoline and LPG fuel.

Certainly the use of advanced 3D CFD [13,14] flow simulation tools could help to describe the relationship between gasoline and LPG injection, but in this case the details of the geometry of both injector nozzles are required. Usually when the LPG fuel system control unit is developed, the details of the design of the gasoline injector are not known precisely. The gasoline injector is treated only as an object in the control system and the global 3D flow characteristics are rather difficult to obtain. In a typical LPG system for a MPI engine the initial settings enables the engine to start, but the dependence of LPG fuel injection duration t_{LPG} on Δp_{BEN} is not considered. The proposed method tries to build a simplified but adequate relationship between t_{LPG}, gasoline injection duration t_{BEN}, and gasoline injection pressure Δp_{BEN}, that enables control of LPG injection on the basis of values read directly from the main ECU of a gasoline direct injection engine:

$$t_{LPG} = f(t_{BEN}, \Delta p_{BEN}) \tag{2}$$

2. Calculation procedure

The evaluation of the relationship between the LPG fuel injection duration t_{LPG} and the gasoline injection duration t_{BEN} read from the original engine control unit was based on the following assumptions: