Gasoline Direct Injection (GDI), Reasons, Operation, and Potentials

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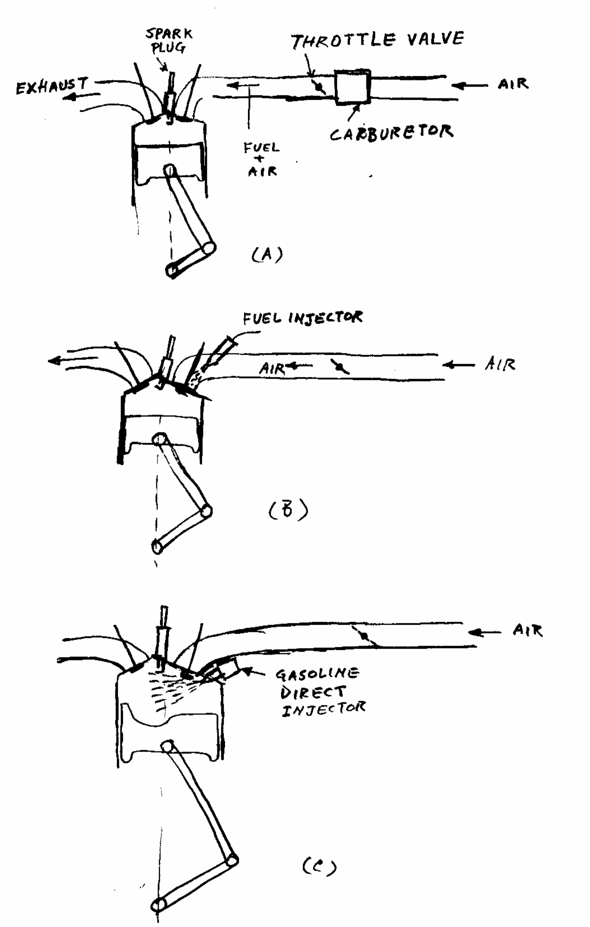
The quest for an even more efficient, smarter, and environmentally-cleaner liquid-fueled spark ignition (SI) reciprocating engine than the current multi-port fuel injection (MPFI) SI engines is more alive and intense now than ever before. In this effort the GDI SI engines have an important and special place. Some background information is of value to facilitate the understanding of the operation and potentials of the GDI engines. The history of the fuel/air mixture preparation system in SI engines starts with the carburetor units positioned in the intake system just prior to the throttle valve which itself is connected to the driver accelerator foot-pedal for manual load (or engine output torque and power) changes in these engines. For many years this served the purpose until the race for the higher performance, more fuel efficient, and cleaner-burn engine intensified that led to the MPFI SI engine design. In this design, an electronically-controlled fuel injector is used per each cylinder for fuel metering and targeting of the sprays towards the intake valves. In MPFI engines the amount of fuel injected can be independently controlled from the air flow and the replacement of the carburetor unit by the port injectors itself caused a better breathing capability (or higher so-called volumetric efficiency) of the engine leading to higher output torque and power levels. Higher volumetric efficiency means that each cylinder of the engine can bring more mass of air thereby providing the potential and opportunity for more fuel introduction and hence higher chemical energy release per cycle delivering a higher engine torque. In contrast, diesel engines use direct liquid fuel injection into the cylinder and rely on autoignition of the fuel itself with no external ignition sources such as spark plug or any other means. The load in these engines are varied by changes in the amount of the fuel injected and there are no throttle valves in the intake system. Therefore, the pumping work, a negative work or energy needed to pump air in and burned gases out of the cylinders, are nearly zero for diesel engines whereas it changes from a maximum value, at idle throttle valve position, to a negligible amount under full load at wide open throttle (WOT) valve position in SI engines. Note that the net indicated output work of an engine is equal to the total work during the compression and expansion strokes minus the pumping work. Pumping work is also referred to as throttling work losses in the automotive literatures. The absence of the throttling work losses (as a result of the lack of the throttle valve) for the direct injection (DI) diesel engine is also one significant advantage of the GDI engine design. This provides an opportunity for improvement in specific fuel consumption (SFC) over the current MPFI engines. In a sense a GDI engine is like a DI diesel engine but with a suitably-positioned spark plug and a gasoline fuel, instead of the easily auto-igniting diesel fuel, in-cylinder injection system. In practice, some degree of throttle control is usually required for GDI engines, compromising the SFC improvement potential.

Full potential of the GDI engine can be harnessed if different in-cylinder fuel distributions can be achieved under different operating conditions. Under the low-load condition such as cruising, an overall-lean but stratified in-cylinder charge is required. A gradual transition from the low-load to an early injection during the intake stroke producing a more homogeneous and stoichiometric in-cylinder air/fuel mixture is needed. This can be approached by a combination of proper designs of the intake ports and chamber geometries to achieve an appropriate chamber flow field, suitable positioning of the spark plug and the in-cylinder injector plus its type, and complex sensors and high-speed computer-controlled control system. Note that the stoichiometric air-to-fuel mass ratio for hydrocarbon fuels of known molecular structure can be determined by an ideal combustion in which only CO_2, H_2O, and N_2 are assumed to be in the products of combustion. A lean mixture has more air per unit mass of the fuel as compared to the stoichiometric air-fuel mixture. The term “overall-lean” means that the ratio of the total mass of the trapped air to that of the injected fuel per cylinder (and per cycle) is lean. However, inside the cylinder of the GDI engines the local air-to-fuel mass ratio distribution is not uniform (i.e. stratified) and spans from the lean to rich mixtures. This overall-lean but stratified-charge distribution is the key to the low-load operation of the GDI engines enabling no or minimum throttling work losses.

Although nearly half of the SFC benefit of the GDI design is through the reduction of the throttling work losses under stratified-charge operation, there are other factors that contribute to the total SFC improvement. Reduced heat losses under the low-load stratified mixture brought by the cooler gases near the cylinder walls is one factor. Because of the vaporization of the liquid gasoline fuel spray injection into the cylinder the averaged in-cylinder temperature is reduced increasing the knock-limited compression ratio, opening an opportunity for increased design compression ratio.[1] Theoretically, it can be shown that thermal efficiency is enhanced (or, equivalently, SFC is reduced) by an increase in compression ratio. This mixture cooling by liquid fuel vaporization also brings about increases in volumetric efficiency through elevated averaged density and hence larger trapped air masses contributing to the overall SFC improvement. Another demonstrated advantages of the GDI engine is faster engine transient response due to less acceleration fuel-enrichment required. Fuel enrichment in MPFI engines is needed during the acceleration to compensate for the delayed transport of part of the injected liquid fuel that is deposited on port and valve wall surfaces. In-cylinder injection eliminates the need for such an extra fuel injection. Also, less cold-start fuel enrichment is needed because of the demonstrated more rapid engine start-up after the first or second cranking cycle for GDI engines consequently reducing the cold-start unburned hydrocarbon (UBHC) exhaust emission. Because of the overall-lean strategy mentioned above under low-load condition the CO_2 emission of GDI engines are also quite low.

Despite the aforementioned advantages there are some potential issues that are being addressed through intense research around the globe. These are, excessive light-load UBHC emission, excessive high-load oxides of nitrogen (NO_x) emission, reduced utilization and effectiveness of the three-way catalysts because of the overall-lean operation, injector deposit issues, complexity of the control and fuel injection technologies for smooth load variation, and soot formation under full-load conditions. For more information, the readers are invited to read SAE technical papers 962018, 960600, 960465, 960465, 970543, and 970627.

[1] Knock in SI engines, Powertrain International, Vol. 1, No. 1, p. 6, 1998.



Schematic diagram of (A) Carburetor engine, (B) Port fuel injection engine, and (C) GDI engine.