Design Rationales for Popular Engines

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In the past hundred years, automotive engineers and researchers have built many reciprocating engines with different designs, of which only a few have survived, became popular, and mass produced. In this tutorial, basic design rationales and their practical implementations are briefly discussed from the perspective of air intake and combustion science and technology.

Obviously, the two most popular designs which survived for many years are the homogeneously–charged gasoline-fueled spark ignition (SI) and the compression ignition (CI) diesel engines. In the SI engines, the design rationale is to prepare a homogeneous mixture of vaporized fuel and air at the time of spark ignition. The start of the combustion is started through a discharge of a sufficiently high amount of electrical energy into the mixture via an ignition system with a spark plug. Mixture preparation is another key element of the engine design. Traditionally, in SI engines, the fuel was fed through a carburetor unit positioned in the air intake system, see Fig. 1. The hope or the goal was to provide each cylinder of an engine with the same and homogeneous air/fuel mixture (or, mass A/F ratio). The engine power adjustment (or throttling) is achieved via a so-called "throttle valve," also located in the air intake system to limit the amount of air (and consequently the fuel mixed with it) inhaled by the engine. Note that the primary reason the power is throttled by controlling the air input mass to the cylinder is the fact that ignition of fuel/air mixtures is readily achieved when they are slightly on the rich side of the theoretical (or stoichiometric) A/F ratio. A rich mixture means that it has more mass of fuel than theoretically needed to completely burn with all the available oxygen molecules in a cylinder. A lean mixture, on the other had, has more oxygen than theoretically needed. Ignition reliability degrades and the required input energy substantially increases when a "lean" fuel/air mixture is formed at the time of ignition. Therefore, in this design, one cannot vary the engine-out power by changes in the fuel flow rate alone (as is done in a diesel engine described later) while satisfying maximum intake air appetite of an engine (i.e., fully-open throttle valve at all times). One major disadvantage of this design strategy is precisely the manner the power in controlled. At wide open throttle (WOT) when the throttle valve is fully open, an SI engine easily inhales the largest amount of fresh air possible in order to generate the maximum output power. However, at all other throttle valve settings (or power settings), being maximum at idle, the engine needs certain amount of work just to bring the air in and send burned gases out of the cylinders. This is referred to as the "pumping work" in engine terminology. In this regard, the SI engine acts somewhat similar to a human respiratory system. If one's nasal passages are restricted (say, as a result of an episode of cold or flu) the act of breathing (i.e., bringing air in and exhaling) becomes quite difficult if one's mouth is not used for this purpose. Minimization of this pumping work has been one key idea behind many other designs, such as stratified-charged or gasoline direct injection (GDI) engines, using gasoline as a fuel. In the past twenty years, there have been improvements in all aspects of the engine design. From the mixture preparation perspective, the important one was the elimination of carburetors and the prevalent application of gasoline multi-port fuel injectors (MPI) injecting at the intake valves. This measure has improved, amongst others, the breathing capability of these engines, consequently delivered higher output power per engine displacement volume than before.

In a diesel engine design strategy, not only the type of the fuel is different but the power adjustment is accomplished through changes in the amount of the fuel alone which, in contrast to SI engines, is directly introduced into the cylinder (i.e., combustion chamber) via a multi-hole very high-pressure injector. In this design, there is no throttle valve and the engine inhales the maximum mass of air into the engine. However, as oppose to SI engines, there is no ignition issue here because it is not achieved through spark energy, rather, the "autoignition" properties of the fuel is the main ignition mechanism. Here, once the liquid fuel is injected, it must be atomized to ligaments and droplets, vaporized, mixed with the air for the autoignition chemistry to begin. After certain amount of time from start of injection, called ignition delay period, ignition occurs spontaneously at multiple locations within the combustion chamber. Due to the nature of the mixture preparation and combustion in diesel engines, higher compression ratios can be achieved to gain better fuel conversion efficiencies than those obtained by SI gasoline-fueled engines. The compression ratio for SI engines is limited by the occurrence of the "knock" phenomenon. Note that the charge in diesel engines is stratified and the major part of the burning is controlled by the fuel-air mixing during a combustion event. In addition, considering that a diesel engine is an overall-lean-burn design, it boosts the combustion and fuel conversion efficiencies.

In recent years, intensive research efforts were spent on direct-injection stratified-charge gasoline engine design. The idea here is to take advantage of benefits of in-cylinder direct injection and be able to reduce or eliminate the pumping work necessary in gasoline SI engines. In other words, the hope is to eliminate the throttle valve and have the engine inhale the maximum amount of air (similar to diesel) but maintain the on-demand and controllable spark initiation feature of the SI engines. This design has two principal operating modes: stratified and homogeneous. The primary difficulty here is the A/F ratio near the spark plug and at the time of ignition. Under stratified operation, the designs of the combustion chamber, intake system, and the in-cylinder injector must be able to provide a rich fuel/air mixture near the spark plug and at the time of ignition, yet be able to achieve an overall-lean combustion for the large portion of the engine operating range. At high to maximum load range, the fuel is injected early during the intake phase and this design operates similar to a homogeneously-charged engine with certain level of intake air control via a throttle valve. After many years of research, this gasoline direct injection (GDI) engine design has achieved most of the aforementioned goals. Engines of this design strategy are largely marketed in Japan and Europe.

Currently, special attention is paid to and research works targeted on a new engine concept called homogenously-charged compression-ignition (HCCI). The idea here is to combine all advantages of the SI and diesel engines and more in one design. This engine is homogeneously charged to virtually eliminate any soot production and runs lean to achieve the highest combustion efficiencies possible. The start of combustion is based on the autoignition chemistry, similar to diesel engine. As such, the importance of turbulence (for flame propagation and/or fuel-air mixing) inside the cylinder is totally lost. Although appears promising, there is no production engine commercialized yet anywhere in the world based on this concept. Detailed characteristics of this research engine have been discussed in a previous tutorial article.

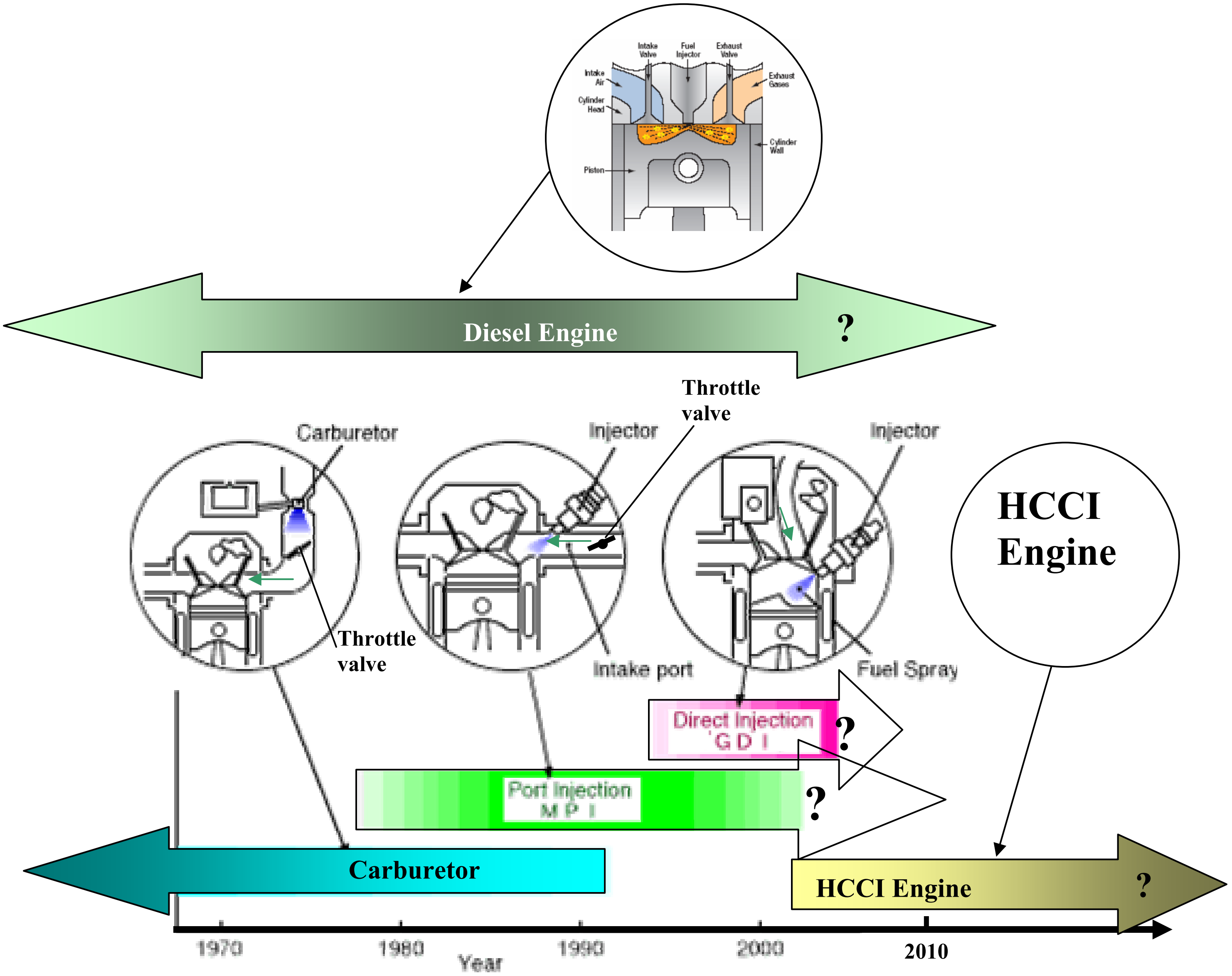

Figure 1. Historical evolution of the gasoline- and diesel-fueled engines indicating different methods of mixture preparation and combustion. Carburetor, MPI, and GDI designs are gasoline-fueled spark-ignited engines.