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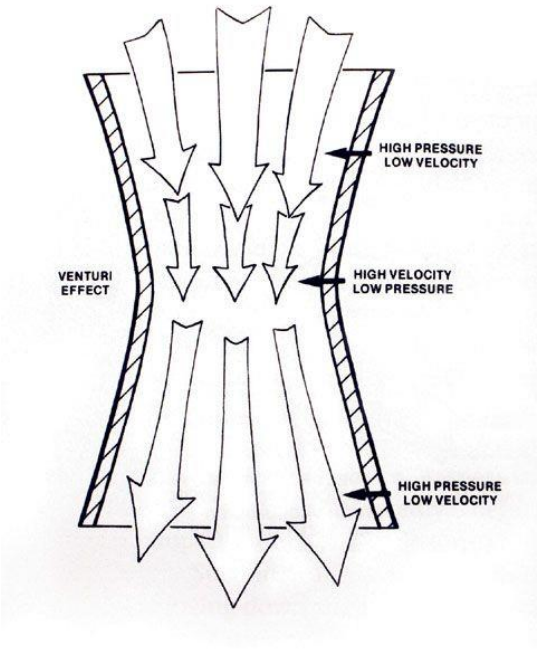
Direct Injection

Abstract

The formula SAE competition makes students push the envelope of performance for small engines to compete against each other in the FSAE competition. Students look at what's new in the automotive and racing industry and see what can be incorporated into their car. One of the newest innovations in the automotive and racing industry is direct fuel injection. Direct fuel injection is one of the big new things car manufactures are incorporating into their new models to improve fuel mileage and performance. Incorporating this new technology into the FSAE car will let the car perform at a higher level of performance and fuel mileage. Since this is new technology that no one has really tried for their FSAE car before we will have to design our own system and see if we can get it working right.

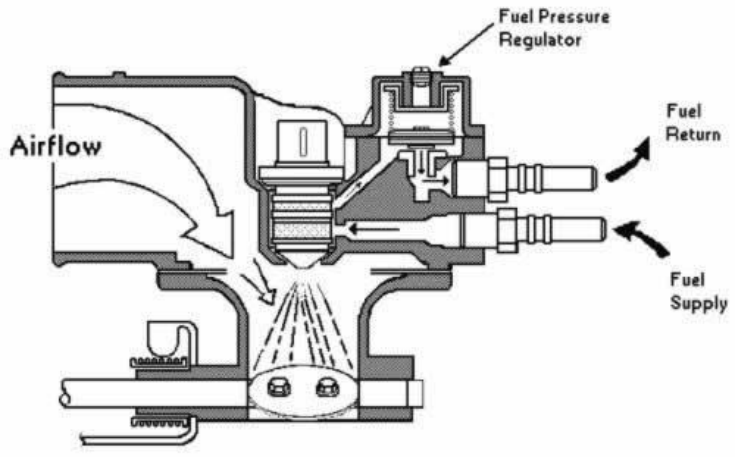
Current Trends

All motors require fuel and air to run, getting air into the engine is not that hard since that is what the motor breathes in but fuel can be tricky to get the fuel to mix with the air to make it useful. The old technology of mixing air and fuel is with a carburetor, which uses the principles of physics via a venturi to meter the right amount of fuel in to



the combustion chamber but it was only tuned for one set of environmental condition so it was not ideal to be used in extreme conditions. The next big step in mixing fuel with air came in the mid 1980's with electronic fuel injection. Electronic fuel injection is far superior to carburetors in the fact that the computer controls how long the fuel injector stays open allowing the correct amount fuel to be injected into the engine to meet the environmental conditions the engine is operating in. There are two main types of electronic fuel injection, throttle body injection (TBI) and the more common port fuel injection. Throttle body injection mounts the fuel injector(s) before the intake manifold and sprays fuel through the intake manifold kind of like how a carb meters fuel into the intake manifold. Port fuel injection mounts the fuel injector in the intake runner and points it toward the back side of the intake valve. Throttle body injection mixes the fuel and air better since the mixture has more time to mix together since it travels through the intake manifold and runner before getting to the chamber where it burns.

In the PFI engine, there is an associated time lag between the injection event and the induction of the fuel and air into the cylinder. The vast majority of current automotive PFI engines utilize timed fuel injection onto the back of the intake valve when the intake valve is closed. During cranking and cold starting, a transient film, or puddle, of liquid fuel forms in the intake valve area of the port. This causes a fuel delivery delay and an associated inherent metering error due to

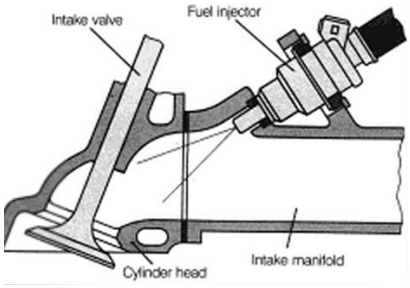


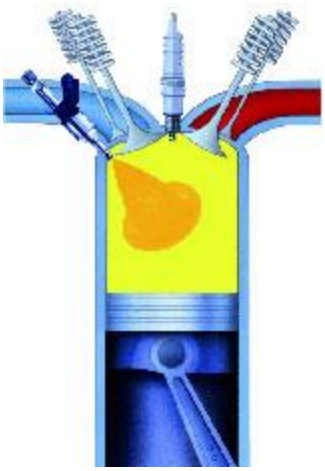
Throttle Body Injection

partial vaporization, making it necessary to supply amounts of fuel that significantly exceed that required for the ideal stoichiometric ratio. (Harrington, 1999, 1)

New Way of Doing Things

For the past couple years the MSU FSAE team has used port fuel injection with 2 injectors, one injector pointed right at the back of the valve like a conventional port fuel injection system and another injector pointing against the airflow to help mix the fuel and air better. This system has worked well but has its drawbacks, the fuel doesn't always mix well with the air and can cause lean and rich spots in the chamber and not burn completely and letting power go out the exhaust pipe due to the fuel pressure only being around 50 PSI. With having an injector in the manifold and intake runner you have to design a wet manifold and runner since there is fuel and air going through the manifold and runner and it is possible to have some of the fuel fall out of the air/fuel mix and form droplets in the runner and not burn efficiently. Using direct injection would solve a lot of those problems since you would only use one injector and since the injector is mounted in the chamber you would not have to design a wet runner and manifold, only a dry one since there is only air flowing through it.





The very low charge motion in this engine speed range results in combustion instability of the MPFI system. This is improved by direct injection, as the high pressure injection atomizes the fuel into

small droplets leading to a stable mixture formation (Trattner, 2012, 8).

Direct injection runs at a much higher pressure then regular fuel injection due to the fact the injector is located in the combustion chamber and has to overcome the cylinder pressure when the piston is at TDC and spinning at 6000 RPM. Injecting fuel at such a high pressure also helps it break down the fuel droplets so it easier for the fuel to mix with the air to get better combustion.

Not so New technology

Direct injection is not as new as some people may think; it was first used over 60 years ago by the air force to help the problem of the deficiency of performance inherent with carburetor systems.

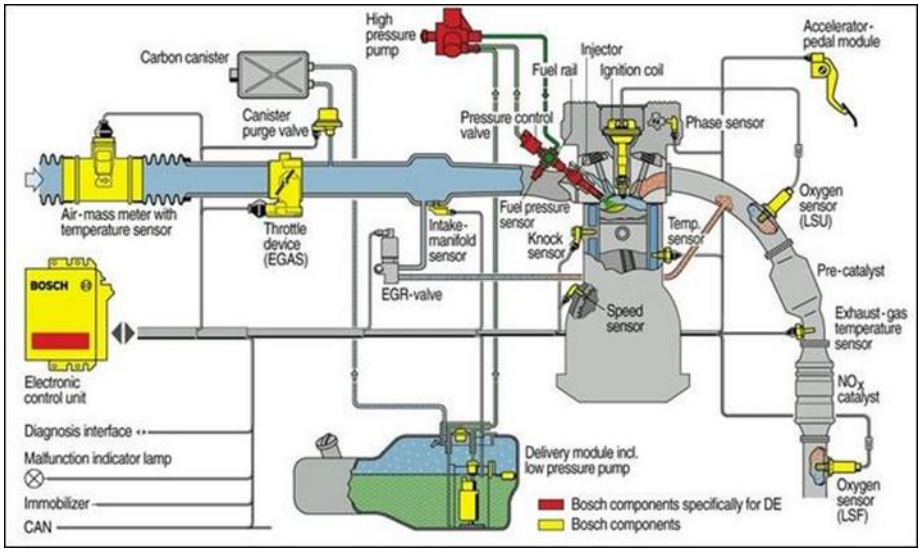
Before the invention of sophisticated carburetors, some of the highly boosted air plane engines adopted direct injection systems using the fuel injection technologies for diesel engines. Consequently, the objective had not been in the fuel economy improvement. (Iwamoto, 1997, 1)

The first direct injection system used a mechanical injector pump to inject the fuel and only could be set to inject the fuel at one preset time, now modern with computer controls we have almost infinite control over the injector to inject the right amount of fuel at the right time.

System Requirements

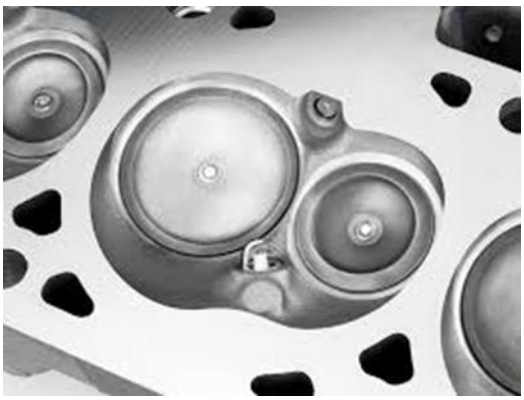
Direct injection has some special system requirements not normally found on port fuel injection. One of these special requirements is having two fuel pumps, this system needs two

fuel pumps because of the high fuel pressure (30,000 PSI), and one pump pumps the fuel from the tank up to the second pump which is the high pressure pump. The first pump in the tank can be run off of electricity but the high pressure pump is usually driven off of the motor via an eccentric on the cam or off the crank with a chain. Running the high pressure pump actually puts more of a load on the engine because it has to spin the high pressure pump but you gain more power with using direct injection so it is worth it to put a little more load on the engine.



Diesels engines have been using a similar system since they were invented and used for diesel fuel more elaborate care should be taken in regards to lubrication and cooling, because gasoline has a lower viscosity and higher volatility than diesel fuel. (Kume, 1996, 5)

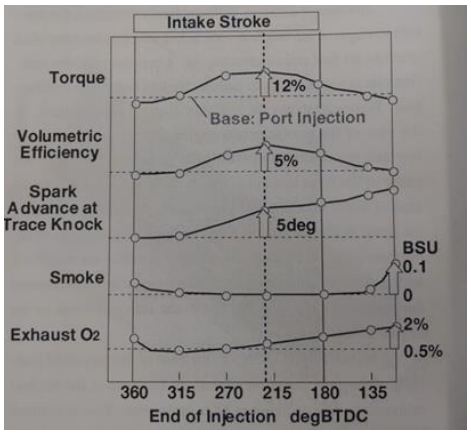
The other major component for a direct injection system the injector itself, it is not like other injectors where you can cast in a port for the injector in the intake runner and it will work. For direct injection to be direct, the injector nozzle has to inject fuel directly into the combustion chamber. The injector has to start from the outside of the cylinder



head and go all the way into the center of the head to the combustion chamber. With placing the injector you have to look at where the cooling jacket is and where the intake or exhaust ports are so you don't run the injector through one of them and restrict airflow. The Combustion chamber already has a lot of components in them like vales and spark plugs and now trying to find retail space for the injector can be tough but if it is possible they reward can be great.

Performance

Direct injection gives you more control to keep you air/fuel ratio in the zone you want for fuel economy or performance and the timing of the injection can have a major impact on how the fuel is burned. The influence of the injection timing can be seen on torque, volumetric efficiency and spark advance during knock tracing, getting more torque and volumetric efficiency is due to the fact that if you inject the fuel early; making it chase the piston down while the intake valve is open and thoroughly mixing evenly throughout the cylinder creating a homogeneous mixture.



Injecting the fuel when the intake air is being sucked into the chamber, the air supplies the latent heat thus causes efficient charge air cooling. When the injection timing of the earliest phase of the intake stroke is selected, fuel spray impinges on the piston. In such a case the volumetric efficiency is the same as that of the port fuel injection engine (Kume, 1996, 12).

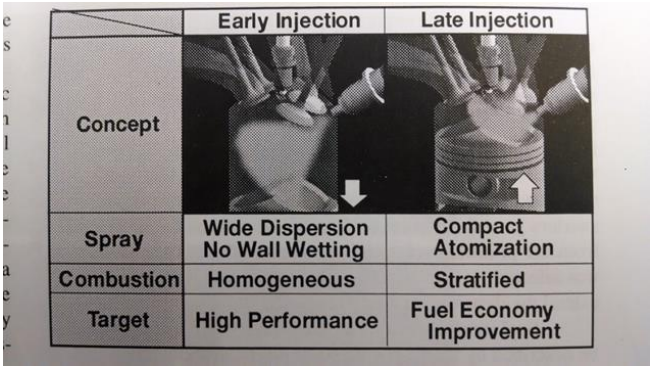
Since the fuel is taking some of the heat from the incoming air, the air gets denser and thus you are able to squeeze more air into the cylinder increasing volumetric efficiency and then you are able to increase the compression ratio of the engine since the air is cooler thus making it more thermal efficient.

Fuel efficiency

Just like with injecting the fuel early to get it to mix thoroughly to make more power, if you inject the fuel late (almost at the top of the combustion stroke) the majority of the fuel (rich spot) will be around the spark plug allowing a leaner air/fuel ratio overall, this is called a stratified charge.

In order to realize its fuel economy potential, the direct injection gasoline engine should run unthrottled in an extremely lean condition by distinctively stratifying the charge and by preparing a rich air/fuel mixture around the spark plug. At part load, when the system can be divided (stratified) into two distinct zones:

- A first with homogeneous air/fuel mixture at stoichiometric ratio, without discontinuities and with distinct boarders, which envelopes the spark source.
- A second zone of pure air , enveloping the first zone, in order to avoid chemical reactions or an intensive heat transfer at the chamber surfaces.(Stan, 1999, 7)



Emissions

When dealing with any new technology in motorsports or the OEMs you have to be thinking and tuning for best emissions, since you cannot release anything to the public without it passing through an emission test. The three main emissions that are targeted are Nitrogen Oxides (NOx), carbon monoxide (CO) and Hydrocarbons (HC). NOx forms when combustion occurs above 2000 degrees Fahrenheit releasing NO in to the atmosphere and when it combines with water can create nitric acid which is acid rain. CO occurs when a rich air/fuel mixture is not completely burned in the combustion chamber. Finally HC occurs when a really rich air/fuel mixture is burned and raw fuel goes out the tail pipe.

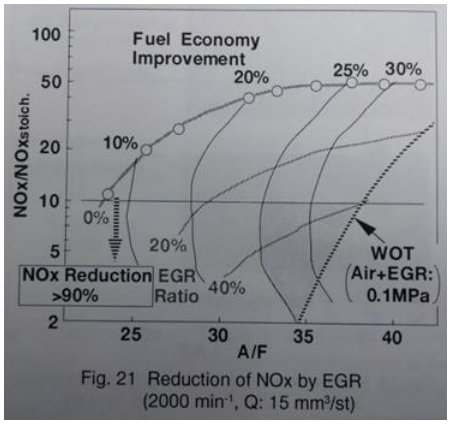


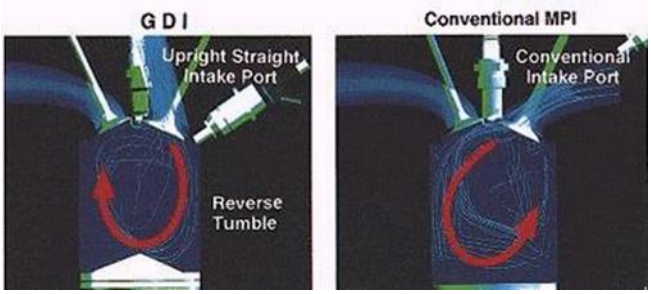
Fig. 21 Reduction of NOx by EGR (2000 min^{-1}, Q: 15 mm^3/st)

The DI process allows for a locally rich region around the spark plug, eliminating the need for enrichment of the entire cylinder to achieve stable combustion. Elimination of rich air/fuel ratios significantly reduces carbon monoxide emissions. (Lorenz, 2005, 2)

The major drawback of direct injection is just like diesel engines, the NOx. Since injecting a small amount of fuel and raising the compression ratio to get better fuel mileage it is going to burn hotter and when it burns hot it produces more NOx.

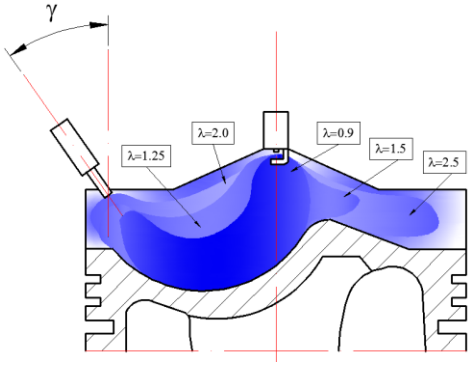
However, stratified combustion has the advantage that the combustion characteristics are not deteriorated by the EGR. Consequently, sufficient NOx reduction can be realized by the introduction of large amounts of EGR (Kume, 1996, 15).

With the use of EGR in direct injection systems the NOx can be brought down as much as 90% and still maintain improved fuel economy over port fuel injection.



Mixing

Getting the fuel to mix is one of the most important aspects of the direct injection system since you have to direct the air to mix with the fuel thoroughly, the most common way to mix the air is to promote tumble in the chamber so the air gets directed toward the injector. To promote reverse tumble it helps to have the intake runner vertical above the chamber and have a



spherical cavity in the top of the piston to also help direct the entering airflow toward the injector. You want a vertical runner as compared to a conventional port fuel injection runner because with the conventional runner the air will enter the cylinder with momentum and hit the cylinder wall and tumble back into its own incoming air stream causing the tumbled air to cut off the air trying to enter the combustion chamber.

Conclusion

Direct injection is one of the most promising new inventions in the internal combustion engine in a great while; It's what all the OEMs are going to on their high end models for both performance and fuel mileage. Subsequently the MSU formula SAE car is about pushing the envelope with new and innovative designs and techniques; currently the FSAE car is utilizing

port fuel injection. Next year the FSAE car will be using direct fuel injection for injecting the fuel. Direct injection gives you the most tune ability to precisely inject the right amount of fuel at the right time to get the most power and fuel economy over the competition. Since direct injection has never really been done in the FSAE competition there will be a lot of hurdles to overcome. The main hurdle will be utilizing the current cylinder head and trying to incorporate a fuel injector into the chamber. The combustion chamber already has valves and a spark plug in there so real estate is tight. Timing the injection pulse is also another major concern, depending if you are going for performance or fuel economy. If performance is the goal then injecting the fuel when the intake air is entering the cylinder (homogeneous mixture)is optimal since the incoming air provides the latent heat for the liquid fuel to atomize and if the fuel is taking heat from the air the air is cooler and more dense so volumetric efficiency goes up along with torque. If fuel economy is the goal then it is optimal to inject vary little fuel almost at top dead center on the compression stroke. Injecting a little fuel right at the spark plug will cause a rich mixture around the plug and a lean mix on the outer edge of the cylinder. When igniting a hot lean mixture, then usually NOx is created. Nox can be majorly decreased by using an EGR valve to displace the incoming air with bunt gasses cooling the mixture. Mixing the whole air/fuel mixture can be a challenge since it does not have a lot of time to completely mix, incorporating something to help tumble the incoming air and directing it at the injector will significantly help the air/fuel to mix. Overall direct injection can be a valuable tool in MSUs arsenal to help with the FSAE competition.

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