Two-Stroke SI Engine Hydrogen Injection Technique

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Abstract
Numerous studies have demonstrated the advantages of hydrogen as a fuel for Otto Cycle engines due to high thermal efficiency and low exhaust pollutant levels. Characteristic of hydrogen engine operation using premixed intake charge formation is a problem of pre-ignition resulting in an intake manifold “backfire”. Additional problems include high NOx production when using certain equivalence ratios and power output degradation due to low fuel energy/volume density. Techniques for direct and port fuel injection are discussed as means for overcoming these problems. Emphasis is placed on the need for total engine control, integrating control of fuel injection, ignition timing, intake air throttling, and vehicle subsystems within a central electronic unit. An electronically actuated fuel injection valve and a prototype electronic control system are developed. These are applied in port and direct injection system geometries, and evaluated in engine testing. System effectiveness and feasibility are discussed.

Keywords: Ignition timing control, quality governing, Hydrogen Injection Technique.

Introduction
The Case for hydrogen as an internal combustion engine fuel has been advanced elsewhere and need not be reviewed in detail here. Briefly, it offers exhaust emissions free of carbon compound pollutants, and increased thermal efficiency. At the same time, it suffers from erratic intake backfire which makes for rough, and sometimes hazardous engine operation when using certain fuel-air ratios, and decreased power output due to the large hydrogen volume fraction of the fuel-air mixture. The backfire problem alone has proven to be one of the key obstacles to practical utilization of hydrogen engines. The low energy of ignition required to initiate combustion of hydrogen and the wide limits of flammability of mixture ratios are primarily responsible for this situation. With air and hydrogen mixed in the conventional carbureted intake system, numerous unintentional sources of ignition are apparently contacted which serve to promote backfire. Water injection, refined ignition systems, and attempts to eliminate random ignition sources have failed to solve the problem of backfire. Injection of hydrogen directly to the combustion chamber offers the promise of greatly reducing and conceivably eliminating the problem. Ideally, delaying any contact of hydrogen and air until just prior to ignition is desired, which would make random pre-ignition (with consequent backfire) impossible. While consideration of charge mixing time and constraints dictated by other aspects of the overall system (pressure available for the injection of hydrogen, for example) make such perfect injection impractical, the injection approach still seems worthy of development. In addition to the potential solution of the backfire problem, it offers improved accuracy of control. Timed injection of the fuel should enhance the effectiveness of controlling the engine operation by varying the fuel-air ratio rather than by intake manifold vacuum. Pumping losses of the latter would be minimized and thermal efficiency increased accordingly. Timed injection would permit taking the fullest advantage of the remarkably wide region of stable combustion between the flammability limits of approximately 8.7 and 75 ~ by volume (29.6 ~ being the stoichiometric).

In terms of the equivalence ratio, ~b, the practical range is 0.23-7.34. The equivalence ratio is defined as the ratio of the actual fuel-air ratio used to the stoichiometric: it is generally used to correlate such variables as ignition energy, flame speed, flammability limits, spark advance, and exhaust gas composition. Obert [3] classifies fuel injection systems for spark-ignited (SI) engines in three categories:
A. Direct cylinder injection

B. Port injection

(a) Timed

(b) Continuous

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C. carburetion Manifold injection or pressure In this work we will focus upon timed injection, either direct to the cylinder or at the intake port just upstream of the intake valve. Continuous injection systems, either at the intake port or as pressurized carburetion will not be considered because they do not allow for separation of the fuel and air intake streams, which is one of the primary objectives of hydrogen fuel injection for suppression of intake manifold backfire. The value of direct cylinder injection for hydrogen has been recognized for some time, having been attempted in the early work of Erren in 1932. He used a third valve to admit the hydrogen from a pressurized source. More recently, Oehmichen, Murrary and Schoeppel Saga and Furuhama and McClean have tested timed high pressure, mechanically controlled direct injection techniques. Swain and Adt have demonstrated a novel "Hydrogen Induction Technique" in which fuel flows through holes in the seat of the intake valve. Their reports based on the performance of a Toyota 1600 powerplant verify the effectiveness of the use of a separate fuel delivery point over premixed charge aspiration in minimization of the ramifications of pre-ignition during the intake stroke. Port injection systems have been in general use on gasoline fueled engines for quite some time. Both mechanically and electronically controlled systems are currently available. Direct cylinder injection of gasoline has been demonstrated on the Mercedes-Benz 300SL and on power plants produced by Goliath and Borgward. It has been generally concluded that the minor advantages of gasoline direct cylinder injection over port injection are not warranted in view of the requirement that the injection valve survive the combustion chamber environment in the direct injection system. Mechanical injection systems have appeared for many years in racing vehicles and in consumer applications. The earliest successful commercial offering of electronic fuel injection appeared in the 1958-59 Chrysler 300 sedan, a Bendix designed system. In 1967, a system produced by Robert Bosch appeared in the Volkswagen Variant model, primarily designed to reduce emissions in the face of 1968 U.S. pollution control regulations. This system offered "computerized" control, and successfully reduced exhaust emissions and improved fuel economy significantly compared to the noninjected model. Systems similar to this now appear in current model vehicles manufactured by Volkswagen-Porsche, Datsun, Volvo, General Motors, Chrysler, Citroen and others.

The flexibility of control offered by the electronic system permits features of fuel shut-off during deceleration, precise fuel metering and cylinder distribution, cold start enrichment, compensation for absolute air pressure (altitude compensation), enrichment for acceleration and full load, overspeed cut-off, and protection from flooding. Automated production processes are now available for rapid individual system calibration. The recent popularity of these systems is due to public and governmental demands for improved fuel economy and reduced emissions. It may be inferred from the commercial success of these systems that design sophistication and economics of production favor the electronic injection system over mechanical. With this observation, and the added control problems associated with backfire suppression in hydrogen fueled engines, it appears that an electronic system offers the greatest promise. With the advent of advanced, low cost digital electronic technology, the implementation of even a very complex control function is often reduced to a problem of appropriate programming of a microprocessor. Hybrid and integrated circuits are finding a rapidly expanding field of application in automotive engine control. Delco division of General Motors offers the MISAR microprocessor based ignition control system on several 1978 model cars. Programmed storage of an experimentally generated engine parameter map could provide for optimal total engine control--injection, ignition, fuel system and vehicle accessories.
Fuel and air introduction mechanism in the modified engine.
(Figure 1)
Since hydrogen and air are premixed in the intake manifold, flashback occurs sometimes under the high load and sometimes at idling. Since the stoichiometric air-fuel ratio is 2.38:1 in volume, hydrogen volume accounts for 1/3 of the piston displacement, while gasoline vapor accounts for only 1/50 of the intake mixture, so the maximum output of the hydrogen engine is only 83% of gasoline output with the same stroke volume.

Higher output than a gasoline engine is obtainable because the amount of mixture is larger since only air is introduced. Due to the absence of the fuel short circuiting during the scavenging process, the fuel economy is improved. The advantage of low NOx formation can be utilized, since a two-stroke engine is inherent of internal EGR. When the temperature of the injected hydrogen is at room temperature, preignitions occurred near the maximum output, but in the case of low temperature hydrogen (-40°C) cooled by liquid hydrogen, pre ignition does not occur. Since there is adequate time from injection to combustion, a sufficient mixing with air is attainable, and thus results in complete combustion. In our system, liquid hydrogen is compressed into a high pressure GH2 tank (10-15 kg/cm2) with a pump, so only a very small amount of the driving power is required, though a large compressor and large power are required in compressing gaseous hydrogen. The endurance of the injection equipment and the liquid hydrogen pump are satisfactory. The car shown in this paper has a two-stroke, three cylinder 550 cc engine, and has a liquid hydrogen storage tank with a capacity of 601. This car can run for 300-400 km with one charge of fuel. In the case of the gasoline engine, the maximum speed of the car is 105 km/h, however we attained 118 km/h as the maximum speed when testing with the hydrogen injection engine. Because the output is 15% more than the gasoline engine, and on account of the large amount of charge, the gear ratio of the differential was modified.

**Quality Governing**

An air-hydrogen mixture will successfully ignite and burn over a wide range of composition. At conditions of 17°C, 1 atm, downward flame propagation in a 1.6 × 30 cm closed firing end tube will take place between limits of 7.7 and 72.6 molar % hydrogen. Corresponding equivalence ratios (\(\Phi\)) are 0.20 and 6.31. This wide range allows the possibility of "quality governing" control in which a power plant may be controlled by varying the fuel-air ratio rather than intake manifold vacuum. As a constant manifold pressure near atmospheric may now be maintained, engine pumping losses, significant under partial...
throttle conditions, are reduced. Thermal efficiency under partial load increases. Quality governing is easily implemented with fuel injection due to the independence of the fuel delivery rate from the air intake rate. This is not the case in carbureted systems; a constant is maintained (theoretically) by the gas mixing carburetor. The engine idling condition is defined by minimum fuel delivery. In a quality governing scheme, a practical minimum equivalence ratio is established slightly above, but near the $\sim b = 0.23$ lean flammability limit. Recommend a minimum practical limit of $\sim b = 0.30$. Experimental engine performance has shown the need for a certain amount of manifold vacuum to establish an acceptable idle. As a quality governed engine incurs minimal pumping losses, only frictional, compression and engine accessory loads establish the idle condition. Operation with very lean values presents problems due to incomplete combustion and long combustion times. Fuel energy is wasted due to incomplete combustion, and a potential backfire condition is created due to residual combustion at time of intake. Reduction of the fuel-air charge energy content below the equivalence ratio of minimum acceptable combustion requires reduction of the air pressure in addition to the fuel fraction, or the use of a charge dilutant such as recirculated exhaust gas. Air pressure reduction is most easily attained and implies the need for some degree of throttling. This throttling would effectively establish a constant equivalence ratio below a certain governor position, as plotted in. The manifold vacuum created, as a pumping loss factor, also assists in maintaining a stable idle speed. A pure quality governed engine behaves much like a two cycle engine in its very gradual deceleration when unloaded. Maximum fuel delivery would optimally be that rate which establishes a $\sim b = 1.0$ intake charge equivalence ratio. Maximum power output is achieved in this case, Consideration of NOx emissions.

Ignition timing control

Combustion flame front velocity for the hydrogen-air mixture is a function of equivalence ratio correlates the data of Breton and Wendlandt on laminar and unstable flame front propagation, respectively. creates a need for greatly advanced ignition timing. Application of quality governing requires the use of low q- mixtures under light loads and engine idling conditions. Long combustion durations and the onset of incomplete combustion determine a practical lower limit on usable equivalence ratio. The rapid flame velocities encountered with rich mixtures ($\sim b$ approaching 1.0) require ignition timing positions at or after TDC to yield satisfactory cylinder pressure distribution over the combustion stroke. Optimum ignition timing is a function of both the fuel-air ratio and the engine speed. For a specific engine, this may not be a simple function that can be readily approximated by a mechanical linkage. Integration of ignition control with injection control provides a straightforward means of maintaining the correct relationship. The desired ignition timing function can be implemented electronically by a central engine control computer, responsible for both injection and ignition system control.

Deceleration fuel cut-off

As an efficiency improving feature, and to avoid the problem of residual combustion on deceleration due to low combustion speeds at low 0 values, but high engine speeds, it is desired that fuel flow be withheld during deceleration transients. A condition of engine rpm greater than the idle value while the governor is in idle position (foot off the pedal) is identified by the electronics as a deceleration condition, and fuel flow is withheld until the idle speed is attained.

Engine over-speed protection: Fuel delivery may be reduced if engine speed exceeds a predetermined value.

Fuel supply control: Master fuel valve shut off is desirable in conditions of engine stall, on-board fire, or vehicle reliever. Detection of a minimum acceptable engine speed, with over-ride during starting, identifies the engine stall condition. Fire or rollover require suitable sensors.

Interactive control of a cryogenic, metal hydride, or chemical hydride fuel storage system: A heating cycle is used for gas withdrawal from a liquid hydrogen vessel. This can be made to respond to engine fuel demands either via line pressure data or in a linear control scheme in which heat admitted to the LH 2 loop is made to track fuel mass flow requirements. A similar control scheme is used in metal hydride storage in which engine exhaust or coolant heat is used for hydrogen release from a hydride bed. In a chemical hydride storage system such as the sodium boro-hydride system, parameters of reaction temperature, solution pH, and catalytic surface area contact are available for control of the hydrogen release reaction. An optimized control
scheme for hydrogen supply in response to engine demand may be implemented through the engine control electronics.

Interactive control of a water injection system, if applied: Water delivery may be tailored to the requirements of the power plant for backfire suppression or NO_x reduction only as actually required. Practically, water injection might be applied so as to track hydrogen flow proportionally or be applied only under conditions of high O and high load.

Special considerations for direct cylinder injection

Direct injection permits fuel delivery after the closure of the intake valve, during the compression stroke. Due to the pseudo-exponential nature of the (ideally) isentropic compression, only a moderate

**Desired Features of a Hydrogen Engine Control System**

Determination of an injector on pulse duration and timing position: Available mechanisms for governing the engine are the injection pulse duration, pressure to the injection valves, and throttle plate position (manifold vacuum control). Pulse duration is determined as a function of:

- Throttle position
- Fuel pressure and temperature at injector
- Manifold air pressure and temperature
- Engine coolant temperature
- Engine speed

As will be discussed later, it is desirable to time the injection cycle so that it always ends at a constant radial position. For direct injection, cycle termination at 90° BTDC in the compression stroke is optimum. This requires generation of a cycle initiation position based upon instantaneous rpm and pulse duration, such that the required injection pulse duration is fitted into the allowed radial duration.

1. Dynamic ignition timing determination using instantaneous engine speed and fuel-air ratio information.
2. Stepped fuel delivery to avoid NOx emissions.
3. Fuel cutoff on vehicle deceleration or coasting.
4. Control of the water injection system, if required.
5. Fuel cutoff in the event of engine stall, on board fire, or vehicle roll over.
6. Dynamic control of the fuel storage and delivery system cryogenic, metal hydride, chemical hydride, alcohol or hydrocarbon decomposition, etc.

(Figure 5)
Conclusions

Delayed fuel delivery, using a timed fuel injection technique either at the intake port or directly into the cylinder is effective in circumventing the problem of backfire into the intake manifold. Electronic control of fuel injection is feasible and may easily provide the control flexibility necessary for optimum overall engine performance. Direct cylinder injection is susceptible to incomplete combustion and high NOx emissions due to heterogeneous charge formation. Mixing improves with rpm due to increased turbulence. Possible improvements in volumetric efficiency by compression stroke injection are offset by thermal efficiency loss due to incomplete combustion. Port injection requires less sophisticated injection valves and avoids the problems associated with incomplete mixing in direct injection. At the present level of the development port injection appears more feasible.

References


[34] M. OEHMICHEN, Wasserstoff als Mortoreibmittel, Verein Deutsche Ingenieur, Deutsche Kraftfahrtforshung, Heft 68, 1942, (as noted in [18]).


