FUELS WITH A HIGH ENTHALPY OF EVAPORATION IN SI ENGINE

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Abstract The increasing use of fuels derived from oil, deepens concern about the fact that non-fossil fuels have to be considered as the fuels of the future. Among the alternatives, hydrogen produced from the abundant sources of water, seems to be one of the best, but it suffers drawbacks with regard to combustion, storage and transportation. The other alternatives are ammonia, produced from unlimited sources of air and water [1], methanol from coal and ethanol from agricultural sources. For operation of the internal combustion engine, lower air-fuel mixture temperature or higher air-fuel mixture pressure are often preferred, because they provide a higher volumetric efficiency and consequently a higher power output. The air-fuel mixture temperature is greaty affected by evaporation enthalpy of the liquid fuel introduced into the inlet manifold of a spark-ignition engine. Due to the very low air-fuel mixture temperature for a fuel such as ammonia, the fuel's change of state may be observed in the inlet manifold. This has a significant role in the operation of the engine. These factors are examined in this paper using related theoretical and experimental results.

Key Words Alternative Fuels, Fuel Evaporation, SI Engines

چکیده مصرف روزافزون سوختهای حاصل از نفت و محدود بودن منابع نفتی، ایجاب می نماید که سوختهای غیر فسیلی بعنوان سوختهای جانشین درنظر گرفته شوند. درمیان این سوختها هیدروژن بدلیل قابلیت تهیه از آب یکی از جانشین های مناسب بنظر میرسد درحالیکه ازنظر احتراق، ذخیره سازی و حمل و نقل دارای نقاط ضعف است. سوخت غیر هیدروکربور دیگر آمونیاک است که ازمنابع نامحدود هوا و آب تهیه میگردد و می تواند بصورت مایع یا بخار به موتور عرضه شود. متانول تولیدی از ذغال سنگ و اتانول از منابع کشاورزی نیز بعنوان سوخت های موتور می توانند بکار روند. برای یک موتور احتراق داخلی، دمای پائین تر و فشار بالاتر مخلوط هوا و سوخت ورودی مناسب تر است زیرا راندمان حجمی و در نتیجه قدرت بیشتری را نتیجه می دهد. بدلیل دمای خیلی پائین برای مخلوط هوا و سوخت هنگامی که سوختی مانند آمونیاک با گرمای نهان تبخیر بالا بکار رود، تغییر فاز برای سوخت ممکن است مشاهده گردد. این امر نقش مهمی در عملکرد موتور دارد. این مقاله با استفاده از نتایج تئوری و عملی مربوطه، به بحث دراین زمینه می پردازد.

INTRODUCTION

Fuel can be introduced into the engine cylinder of an internal combustion engine in the form of liquid or vapor phase. This becomes particularly important when the enthalpy of evaporation of the fuel is relatively high and is introduced into the inlet manifold of a spark ignition engine.

The air-fuel mixture temperature considerably decreases as the fuel evaporates. The degree of evaporation depends on the evaporation enthalpy of the fuel, saturation pressure-temperature relationship, and the heat transfer rate to the liquid. Under these conditions the engine will normally have a higher volumetric efficiency and a higher power output provided that the air-fuel mixture temperature is such that a uniform flow of fuel is provided and combustion is secured. (See Figures 1 and 2).

PREVIOUS STUDIES

Several experimental tests have been performed, to evaluate the parameters affecting fuel behaviour in the inlet manifold and cylinder of a spark ignition engine. It is found that some part of any liquid fuel introduced into the inlet manifold will evaporate depending on the fuel and heat available to it.

Some alternatives to the hydrocarbon fuels have been found. Chelliah [2] and Francis [3] used alcohol fuels as

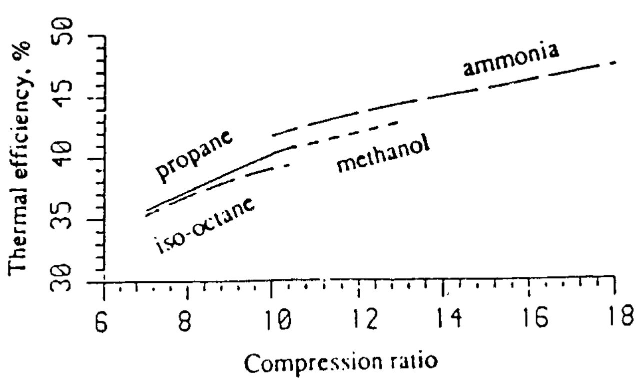

Figure 1. Variation of indicated thermal efficiency with compression ratio at an equivalence ratio of 1.0 and an engine speed of 2000 r/min

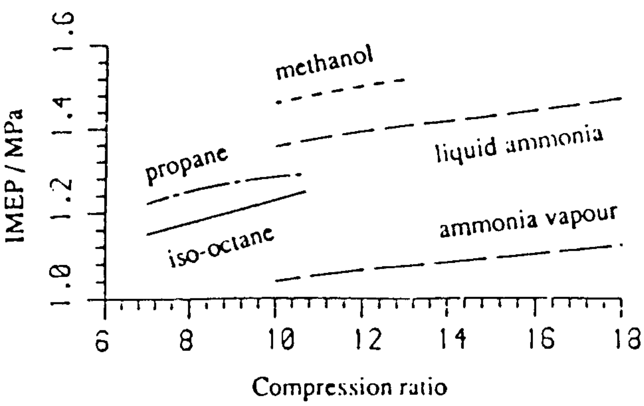

Figure 2. Variation of indicated mean effective pressure (IMEP) with compression ratio at an equivalence ratio of 1.0 and an engine speed of 2000 r/min

internal combustion engine fuels. They concluded that these are cleaner fuels with lower exhaust oxides of nitrogen, and produce less gums and carbon deposits on the engine cylinder walls, but have difficulties regarding cold starting and vapor locking. Introduction of gasoline and methanol into the engine inlet manifold will result in a good performance and smooth combustion. For these fuels the fraction of fuel evaporated at the inlet manifold spontaneously after the introduction, depends on the running conditions and determines the manifold temperature. The experimental data from conditions expressed by Mozafari [4], at stoichiometric air-fuel ratio, shows the inlet manifold temperatures of about 11°C and 0°C for gasoline and methanol respectively. See Appendix A for details of the engine and the test bed layout.

For liquid propane introduced into the inlet manifold, quite a poor engine performance was obtained. High evaporation enthalpy for propane was blamed for its adverse effects mainly because of providing a non-homogeneous air propane mixture. Measurements showed a high unburned fuel concentration in the exhaust gas. Mozafari concluded that for rich air-propane mixtures (fuel-air equivalence ratio $\phi > 1.2$), the high evaporation enthalpy of fuel, provided inlet temperatures so low that the liquid fuel entering the cylinder at this range of ϕ did not significantly affect the air flow.

For liquid ammonia, combustion was achieved with difficulty due to its narrow flammability range. The problem was compounded by the effect of a very low inlet mixture temperature, in some cases reaching as -56°C. Such a low temperature resulted from partial evaporation of the liquid ammonia at the inlet manifold. According to the laboratory observations, the very high evaporation enthalpy of ammonia resulted in freezing problems and consequently partial blockage of the fuel jet. The use of a jet heater located at the jet exit (see Figure 3) proved to be effective, causing a continuous flow of fuel.

Other investigators [5-10] have reported the successful operation of internal combustion engines using ammonia as the sole fuel or ammonia plus additives.

Gray [11], injected liquid ammonia directly into the cylinder of a Cooperative Fuel Research (CFR) compression ignition engine. The engine speed was 900 r/min with the inlet air and cylinder jacket temperature of 149°C. The engine ran steadily with a maximum cylinder pressure of 15240 kPa. At a lower compression ratio of around 30:1 the ignition was impossible.

Mozafari [12] has carried out an investigation on heat transfer rate variation with fuel air equivalence ratio for a number of fuels, using equations proposed by Annand [13] and Rao [14], and the effects of physical and chemical properties of different fuels on Prandtl number were studied. According to the results obtained the evaporation enthalpy of a fuel should be considered as a decisive parameter when heat transfer study is concerned (see Figures 4 and 5).

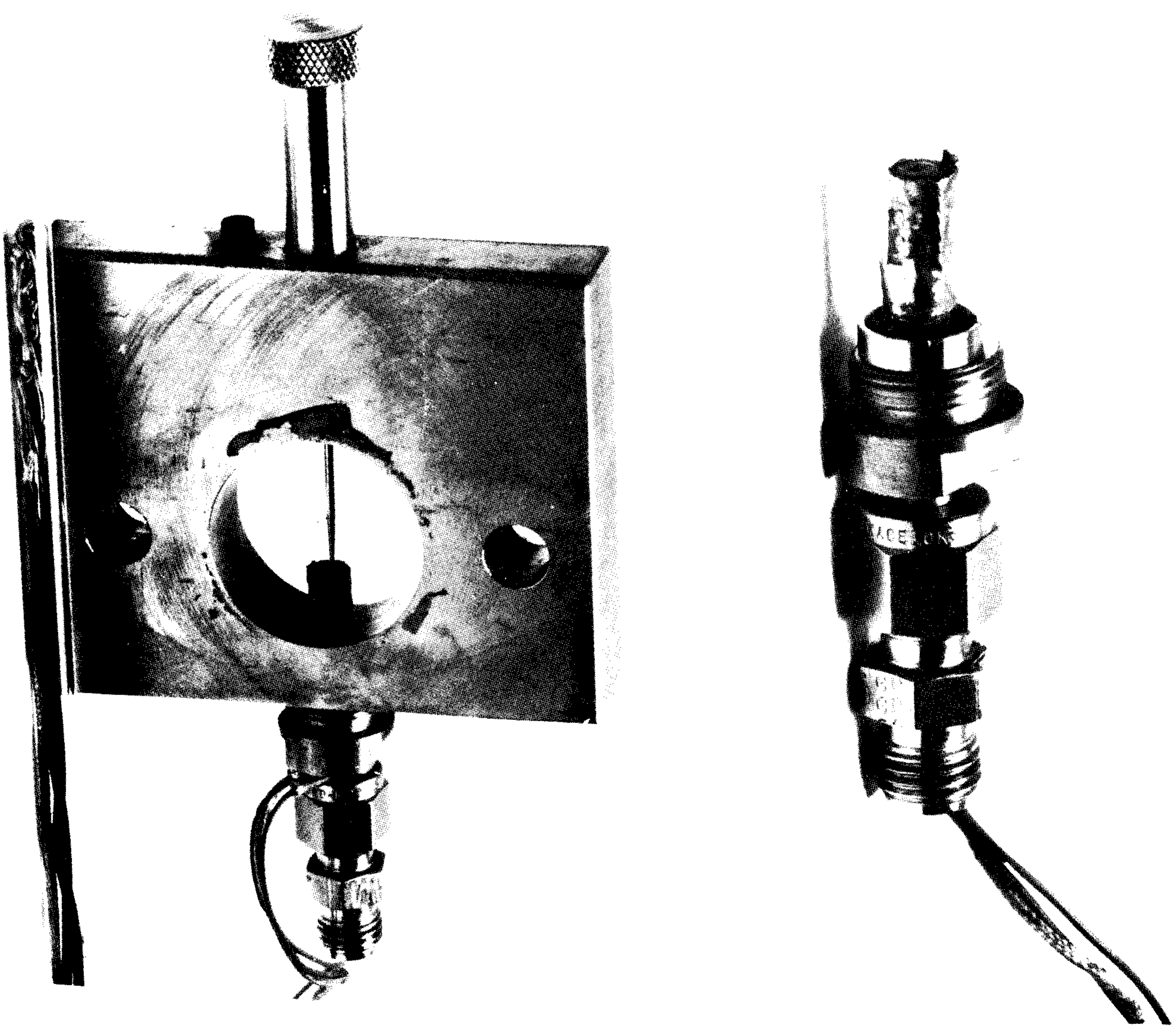

Figure 3. Photograph showing fuel jet and accessories

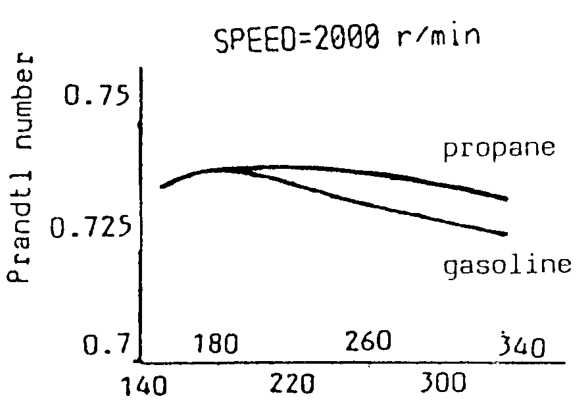

Figure 4. Variation of Prandtl number with crank-angle for gasoline and propane

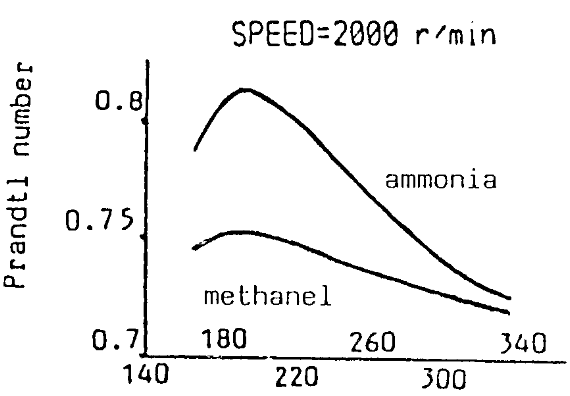

Figure 5. Variation of Prandtl number with crank-angle for methanol and ammonia

The use of pure ammonia without any additive in a spark ignition engine at a normal compression ratio of 15:1, makes it more important to consider ammonia as a reasonable substitute fuel. This necessitates the evaluation of the effects of high enthalpies of evaporation on engine performance.

COMPUTATIONAL STUDY OF FUEL EVAPORATION

Theoretical calculations have been performed to find the fraction of the fuel evaporated in the inlet tract of the spark ignition engine. The variety of fuels considered contain gasoline, a normal fuel for a spark ignition engine, propane, a fuel with a high saturation pressure under a normal laboratory temperature, methanol, an alcoholic fuel with a very high enthalpy of evaporation, and finally ammonia, a fuel with a very high enthalpy of evaporation but with high saturation pressures under normal temperatures. The experimentally-obtained data from Mozafari [4], as well as physical properties of the fuels involved, from JANAF [15] and Rose [16], have been used to assess the percent of fuel evaporation at the inlet manifold. the results obtained have been presented in Table 1.

When a liquid drop almost at ambient temperature is injected into an air stream to the inlet manifold, the following phenomena govern the history of the drop:

a) Deceleration of the drop due to aerodynamic drags
b) Heat transfer to the drop from the surrounding particles
c) Mass transfer of vaporized fuel away from the drop.
d) Change of temperature for evaporating molecules and their surrounding particles.

In such cases, contrary to what happens when the fluid is injected directly into the cylinder, the temperature of the drops decreases as liquid fuel partially evaporates in the inlet manifold at a fairly constant pressure of 1 atmosphere.

The saturation pressure-temperature relationship and the evaporation enthalpy of the fuel from one side, and the local heat transfer rate to the inlet manifold from the other side dictate the droplet behaviour which may be totally

Table 1. Manifold Temp. and Percent of Fuel Evaporation in the Inlet Manifold

fuel	Gasoline	Ammonia	Propane	Methanol
manifold temp.°C	12	-30	12	10
fuel evap. %	34	34	32	6.5
manifold temp. °C	10	-45	10	0
fuel evap. %	45.5	45	43	14.7
manifold temp. °C	8	-60	8	-10
fuel evap. %	57	55	53	23
boiling point °C	99.3	-34	-45	65
freezing point °C	-107.38	-78	-187.7	-93.9

different from that of a normal hydrocarbon fuel injected into an engine cylinder. Thus the present computational theories of evaporation, heat and mass transfer for drops (developed for in-cylinder calculations such as those proposed by Wu [17] and Reitz [18]) would not be applicable.

The present theoretical model presented here, employs the first law of thermodynamics (steady state steady flow) to find the percent of fuel evaporation at the inlet manifold, using the experimentally-obtained data. Air and liquid fuel at their initial conditions (just before fuel injection) were considered as the inlet flows to the system and the air-fuel mixture at the exit condition was considered as the outlet flow from the system. The measured inlet and outlet flow rates plus the related properties resulted in calculating the inlet and outlet velocities (neglecting the ignorable volume of the unevaporated fuel droplets at the exit as a simplifying assumption). The heat transfer from the manifold surface area was calculated using measured experimental data but heat transfer between evaporating droplets and air molecules or other droplets was considered as the system interaction because the aim of research was not instantaneous analysis of droplet size but finding the percent of fuel evaporation at the manifold exit.

The calculations for gasoline show a fuel evaporation of approximately 35% of that introduced. At a higher air-fuel ratio, a higher air-fuel mixture temperature is obtained at the inlet manifold, indicating a smaller quantity of fuel evaporated. In fact, a higher air-fuel ratio corresponded to a smaller quantity of fuel introduced and also a smaller fraction of fuel evaporated.

For methanol, theoretical calculations show a fuel evaporation of about 7% for lean mixtures up to a quantity of nearly 23% for rich mixtures.

For propane, similar calculations show some 40% to 55% fuel evaporation at the inlet manifold depending on the air-fuel ratio. The higher fractions related to the richer conditions.

For liquid ammonia, the percent of fuel evaporation is from 40% at fuel-air equivalence ratio of about 0.88, up to 55% for the richest point corresponding to fuel-air equivalence ratio of about 1.147.

DISCUSSION

As seen from the results presented in the previous section, liquid fuel will partially evaporate at the inlet manifold of a spark ignition engine. The degree of evaporation depends on factors relating to the fuel's physical properties and the heat transfer rate to the fuel.

The heat required for evaporation, will be provided by the particles surrounding the evaporating molecules. Part of this heat is normally regained by particles through conductive, convective and radiative heat transfers from the inlet manifold wall surface. The remaining part of the heat will result in a reduction of the internal energy of the particles.

For a fuel with a relatively low evaporation enthalpy and with a normal saturation pressure at laboratory temperature, (such as gasoline), the reduction in internal energy is low, causing a small reduction in air-fuel mixture temperature. In case the fuel evaporation enthalpy is high, (such as with methanol), a bigger drop in air-fuel mixture temperature will result and if the fuel freezing point is high enough, there will be no fuel feeding problem.

For a fuel with a relatively low enthalpy of evaporation, but with a high saturation pressure at laboratory temperature (such as propane), the process of evaporation will be encouraged by an introduction pressure of about 100 kPa at the inlet manifold. In fact all of the injected fuel molecules would have completely evaporated if the required heat could have been absorbed by evaporating particles. But in practice, the rate of evaporation is restricted and determined by the fuel flow rate and the heat transfer rate to the fuel. Normally some part of the fuel is able to absorb the available heat and thus evaporate, but the remaining part in the from of fine droplets will find its way to the cylinder. Apparently these droplets will gradually evaporate during compression as soon as they can absorb the required heat for evaporation. This group of fuels has the benefit of a higher volumetric efficiency mainly for two reasons, first, a lower air-fuel mixture temperature, second, a smaller volume of the cylinder occupied by the fuel droplets. Since the fuel enthalpy of evaporation is relatively low, a small drop in air-fuel mixture temperature is normally observed with no difficulty regarding the initiation and promotion of combustion.

For fuels with a high enthalpy of evaporation and with a relatively high saturation pressure at laboratory temperature (such as ammonia), the rate of fuel evaporation is encouraged by a lower pressure at the inlet manifold, causing a very low air-fuel mixture temperature at the inlet manifold. In such cases, the required heat for evaporation is rather high. A minor part of the heat is supplied by the heat transfer through the wall surfaces of the inlet manifold. But the major part is to be provided by the particles surrounding the evaporating molecules, causing a very low mixture temperature. In the case of a fuel with a relatively high freezing point, a non-steady flow of fuel may be experienced. This is due to a freezing of particles at the location of jet exit. The frozen molecules will eventually block the jet exit area, preventing the normal flow of fuel. A decreased fuel flow rate caused by the blockage results in less fuel evaporation and consequently less heat required for evaporation. However, the air-flow rate remains relatively unchanged. The heat conveyed by air now overcomes that needed for the present lower evaporation heat, thus the excess heat tends to melt the frozen particles causing a higher rate of fuel flow until blockage is eliminated and a normal fuel flow is again restored. The whole process will again be repeated causing a pulsating fuel flow rate and a non-uniform engine performance. Such a problem could be overcome by use of a jet heater similar to that shown in Figure 3.

The power required for such a heater is very low. A heating power of 10 Watts showed to be sufficient for the conditions reported by Mozafari [4]. This power is less than 0.05% of the enthalpy of the fuel introduced into the engine. Such a low heating power can be supplied by a very small heater mounted in any fuel supply system.

CONCLUSION

Hydrocarbon fuel sources are limited and suitable alternatives are needed. Alternative fuels with non-oil sources are preferred. Ammonia, synthesized from natural raw materials may be a substitue fuel. It can be introduced in the from of liquid directly into the cylinder of a compression ignition engine with a compression ratio of 35:1. Ammonia can also be introduced into the inlet tract of a spark ignition engine in the form of either liquid or vapor phase. The former gives a lower inlet air temperature with a gain of up to 20% in power output and a volumetric efficiency over those obtained with vapor ammonia.

At the same compression ratio, the specific fuel consumption with ammonia would be about 2.3 to 2.4 times that with hydrocarbon fuels (gasoline or diesel fuel). Thus in the case of ammonia a bigger fuel tank (ammonia cylinder) is needed.

Regarding air pollution, in the case of using ammonia, traces of carbon mono-oxide, carbon dioxide and unburned hydrocarbons (due to the burning of lubricating oil) and also very low concentrations of oxides of nitrogen and unburned ammonia will be present in the exhaust gas.

Fuel with a very high enthalpy of evaporation may be used as a fuel in the spark ignition engine. It can be introduced into the inlet tract in the form of liquid phase. Feeding problems may be experienced if the saturation pressure of the fuel at normal temperatures is relatively high (such as with ammonia). This is due to the fact that the rate of fuel evaporation will be encouraged by the manifold atmospheric pressure. In such cases feeding problems in the form of freezing at the jet exit may be observed. Local heating should be provided to prevent the effects of fuel-flow blockage caused by freezing. The heating power requirement is less than 0.05% of the enthalpy of the fuel introduced. Using this method the engine needs a compression ratio of 15:1 compared to a ratio of 35:1 for the same fuel in a compression ignition engine.

Liquid fuels with a very high enthalpy of evaporation and with normal saturation pressure at ambient peratures (such as methanol) will result in a higher volumetric efficiency and provide no difficulty regarding the initiation and promotion of the combustion.

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APPENDIX A

Engine type: Ricardo E6/R

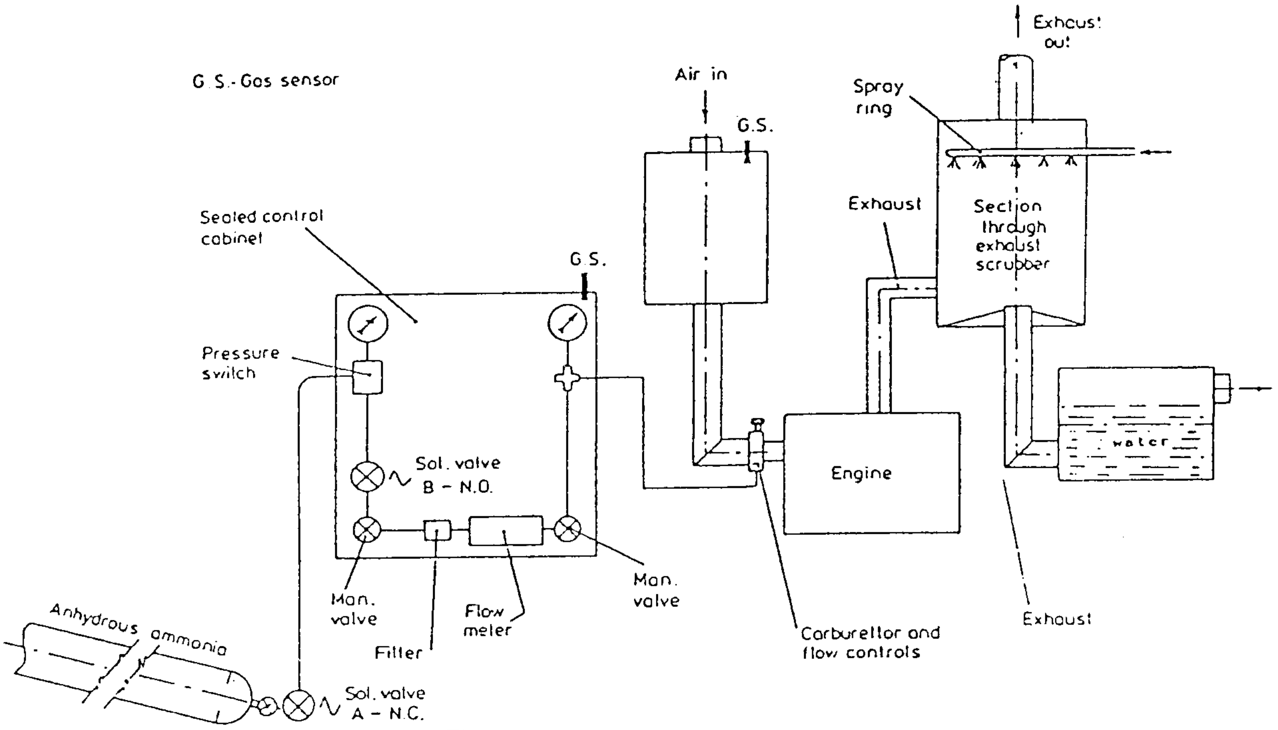

Figure A1. Schematic view of test bed

Single cylinder, four stroke, spark ignition cylinder head.
Compression ratio (variable from 4.5: 1 to 20:1)
bore: 76.2 mm, stroke: 111.1 mm, connecting rod length: 231.7 mm
Engine lubricating system: wet sump type.
Engine cooling system: semi-closed loop
Engine ignition system: magneto type capable of varying spark in a range from 0 to 100 degrees advance before TDC.
Engine fuel supply system: specially designed to inject the liquid fuel (under pressure in the storage tank) to the inlet tract after the Solox carburettor. The fuel system was capable of withstanding pressures in excess of 2 MPa.