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BIOGAS FUEL FOR INTERNAL COMBUSTION ENGINES

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SUMMARY

Author presents the problems of biogas use for powering internal combustion engines. Modification of internal combustion engines for stationary electrical generators and internal combustion engines for tractors and light duty trucks is reviewed.

Properties and desired characteristics of biogas fuel are also presented. The main aspect of stationary internal combustion engines for electrical generators use is for isolated farms and rural areas, which is now thoroughly examined through techno-economical analysis and impacts on environment.

KEY WORDS:
biogas, engine, electrical energy

INTRODUCTION

Current energy situation throughout the world and the fact that main resources of energy, such as crude oil, natural gas, coal and nuclear fuel are not renewable give importance to other sources of energy, like hydro energy, solar energy, energy of wind and biogas. Mentioned sources of energy are all renewable, but biogas is particularly significant because of possibility of use in internal combustion engines, which are the main power source for transport vehicles and also commonly used for powering of generators of electrical energy. This possibility of use is justified by biogas' properties, which make it convenient for IC engines.

PROPERTIES OF BIOGAS AS FUEL FOR INTERNAL COMBUSTION ENGINES

Biogas is the product of fermentation of man and animals' biological activity waste products when bacteria degrade biological material in the absence of oxygen, in a process known as anaerobic digestion. Since biogas is a mixture of methane (also known as marsh gas or natural gas) and carbon dioxide it is a renewable fuel produced from waste treatment.

Biogas contains 50% to 70% of CH_4, 2 % of H_2 and up to 30 % of CO_2. After being cleaned of carbon dioxide, this gas becomes a fairly homogeneous fuel containing up to 80 % of methane with the calorific capacity of over 25 MJ/m^3. The most important component of biogas, from the calorific point of view, is methane, CH_4. The other components are not involved in combustion process, and rather absorb energy from combustion of CH_4 as they leave the process at higher temperature than the one they had before the process. Requirements to remove gaseous components depending on the biogas utilization are in Tab. 1 (Hingerl, 2001).

Tab. 1 Requirements to remove gaseous components depending on the biogas utilization

Application	H_2S	CO_2	H_2O	Siloxane
CHP engine	< 500 ppm	no	no condensation	yes
Vehicle fuel	yes	recommended	yes	no

Thermodynamic properties of CH_4 at 273 K and 101325 Pa are:

- specific treat c_p = 2,165 kJ/kgK
- molar mass M = 16,04 kg/kmol
- density ρ = 0,72 kg/m^3
- individual gas constant R = 0,518 kJ/kgK
- lower calorific value H_u = 50000 kJ/kg, $H_{u,n}$ = 36000 kJ/ m^3n

The actual calorific value of biogas is function of the CH_4 percentage, the temperature and the absolute pressure, all of which differ from case to case. The actual calorific value of biogas is a vital parameter for the performance of an engine, and can be calculated by using the following equation:

$$H_{u,act} = \frac{V_{CH_4}}{V_{tot}} \cdot \rho_{CH4,act} \cdot H_{u,n} \ .$$

The fuel consumption of IC engine using biogas is often specified in m^3n/h or m^3n/kWh. The standard cubic meter (m^3n) means a volume of 1 cubic meter of gas under standard conditions (273 K and 10132 Pa). The consumption of biogas in actual volume will differ from these data according to the actual conditions of biogas fed to the engine in terms of temperature, pressure and CH_4 content.

Determining of actual biogas consumption is vital for dimensioning the engine.

Technical parameters of biogas are very important because of their effect on the combustion process in an engine. Those properties are:

- Ignitability of CH_4 in mixture with air:

CH_4: 5...15 Vol. %

air: 95...85 Vol. %

Mixtures with less than 5 Vol. % and mixtures with more than 15 Vol.% of CH_4 are not properly ignitable with spark ignition.

- Combustion velocity in a mixture with air at p = 1 bar:

cc = 0.20 m/s at 7% CH4

cc = 0.38 m/s at 10% CH4

The combustion velocity is a function of the volume percentage of the burnable component, here CH_4. The highest value of c_c is near stoichiometric air/fuel ratio, mostly at an excess air ratio of 0,8 to 0,9. It increases drastically at higher temperatures and pressures.

- Temperature at which CH_4 ignites in a mixture with air T_i = 918K ... 1023 K
- Compression ratio of an engine, e, at which temperatures reach values high enough for self-ignition in mixture with air (CO_2 content increases possible compression ratio) e = 15...20
- Methane number, which is a standard value to specify fuel's tendency to knocking (uneven combustion and pressure development between TDC and BDC). Methane and biogas are very stable against knocking ad therefore can be used in engines of higher compression ratios than petrol engines
- Stoichiometric air/fuel ratio on a mass basis at which the combustion of CH_4 with air is complete but without unutilised excess air

MODIFICATION OF INTERNAL COMBUSTION ENGINES
THE GAS DIESEL ENGINE

Diesel engines can be modified to operate on biogas in two different ways:

- dual fuel operation with ignition by pilot fuel injection,
- operation on gas alone with spark ignition.

THE DUAL FUEL ENGINE

In this case, the normal diesel fuel injection system still supplies a certain amount of diesel fuel. The engine, however sucks and compresses a mixture of air and biogas fuel which has been prepared in external mixing device. The mixture is then ignited by and together with the diesel fuel sprayed in. The amount of diesel fuel needed for sufficient ignition is between 10% and 20% of the amount needed for operation on diesel fuel alone. Operation of the engine at partial load requires reduction of the biogas supply by means of a gas control valve. A simultaneous reduction of airflow would reduce power and efficiency because of reduction of compression pressure and main effective pressure. So, the air/fuel ratio is changed by different amounts of injected biogas. All other parameters and elements of diesel engine remain unchanged.

Modification of diesel engine into dual fuel engine has the following advantages:

- Operation on diesel fuel alone is possible when biogas is not available
- Any contribution of biogas from 0% to 85% can substitute a corresponding part of diesel fuel while performance remains as in 100% diesel fuel operation

- Because of existence of a governor at most diesel engines automatic control of speed/power can be done by changing the amount of diesel fuel injection while the biogas flow remains uncontrolled. Diesel fuel substitutions by biogas are less substantial in this case.

There are certain limitations:

- The dual fuel engine cannot operate without the supply of diesel fuel for ignition
- The fuel injection jets may overheat when the diesel fuel flow is reduced to 10% or 15% of it's normal flow. Larger duel fuel engines circulate extra diesel fuel through the injector for cooling

To what extent the fuel injection nozzle can be affected is however a question of it's specific design, material and the thermal load of the engine, and hence differs from case to case. A check of the injector nozzle after 500 hours of operation in dual fuel is recommended.

MODIFICATION OF A DIESEL ENGINE INTO A GAS OTTO ENGINE

This modification involves a major operation on the engine and the availability of certain parts, which will have to be changed. These alterations are:

- removal of the injector pump and injector nozzles
- reduction of the compression ratio to ε = 10...12
- mounting of an ignition system with distributor (cum angular gear), ignition coil, spark plugs and electric supply (alternator)
- provision of a mixing device for the supply of an air/fuel mixture with constant air/fuel ratio (Venturi mixer or pneumatic control valve)

PERFORMANCE AND OPERATION PARAMETERS

The performance of diesel gas engines in dual fuel mode has been found o be almost equal to the performance using diesel fuel alone as long as the calorific value of biogas is not too low. The inlet channel and manifold of diesel engine are dimensioned in a such way that at the maximum speed and power output of the engine sufficient air can be sucked in to obtain an air/diesel fuel ratio, which is optimal for operation at this point. When the diesel fuel is reduced and an air/biogas mixture is sucked instead of air alone, part of the air is replaced by biogas. With less air fed to the engine ad an excess air ratio necessarily maintained at λ = 1,2...1,3 the total fuel input will be less than the fuel input in diesel operation. As a result in this reduction in both air and fuel, the maximum power output at high speed in dual fuel mode may be less than in diesel fuel operation. This decrease is less significant than in modified petrol engines. For operation in medium and low speeds the air inlet is larger than necessary and allows a relatively larger amount of air/fuel mixture to be sucked in. Hence the power output will not be significantly lower than in diesel operation.

THE GAS OTTO ENGINE

The modification of an Otto engine is comparatively easy as the engine is designed to operate on an air/fuel mixture with spark ignition. The basic modification is the provision of an air/gas mixer instead of carburettor. The engine control is performed by the variation of the mixture supply. An increase in compression ratio appears to be desirable as it provides an increase of the process from the thermo-dynamical point of view. Lower specific fuel consumption and a higher power output can be expected. The modification is permanent and prevents using of original fuel. The adjustment of the point of ignition in the relation to slow burning velocity of biogas imposes no specific problem as a standard ignition system provides for adjustments in a sufficiently wide range. Engines, which cannot operate on unleaded fuel, will miss the lubrication effect of condensing lead especially on their exhaust valves. They are therefore subjected to increased wear and tear in gas operation.

PERFORMANCE AND OPERATION PARAMETERS

Biogas Otto engines when modified from Otto engines using petrol fuel are found to produce less power than in petrol version. The reason is decrease in volumetric efficiency as a gaseous fuel occupies a larger portion of the mixture’s volume sucked into the engine than liquid fuel and displaces air accordingly. The liquid fuel has a higher volumetric energy content than biogas and also cools the air/fuel mixture when evaporating in intake manifold. The cooling effects an increase in density, and hence the amount of air/fuel mixture actually sucked into the engine on a mass basis is higher.

A gas engine, especially when operating on biogas with a large proportion of useless carbon dioxide, can suck a reduced amount of air only to allow room for the necessary amount of fuel gas. As in Otto engines an excess air ratio of $\lambda = 1 \pm 0.1$ has to be maintained and the inlet ducts and manifolds are dimensioned for operation with petrol, the total fuel energy in a mixture of biogas and air is less than in petrol operation. With the decrease in the maximum possible supply of fuel energy for the energy density of the mixture (mixture heating value) the maximum power output consequently decreases in the same proportion. The rate of decrease in power is largely dependent on the volumetric heating value of the gas, e.g. biogas with 70% CH_4 has a higher volumetric calorific value than biogas with 50% CH_4 only. The power output of an engine is therefore higher in operation on gases with high calorific value than in operation on "weak" gases. Biogas (60% CH_4) with a calorific value of H_u = 25 000 kJ/nm³ ranges as a medium weak gas and causes power reductions of about 20% (purified methane or natural gas 10%, LPG 5%). The main effect of the reduction of power is that it needs to be well considered when selecting the power class of an appropriate engine for a given application with a specified power demand. The engine's power and speed control is performed by a variation of the supply of the air/fuel mixture to the engine. This is achieved by the operation of a butterfly valve situated between the actual mixing device and the engine inlet. Closing the butterfly valve effects a pressure drop (throttling effect) in the flow of the mixture by which the cylinder is filled with a mixture at lower pressure, hence with a lower amount of air/fuel mixture on a mass and energy basis. As a result the power output, the mean effective pressure and the efficiency decrease in controlled (partial load) operation. The effect of the decrease in efficiency is realized in an increase of the specific fuel consumption in partial load operation. To compensate for the above-mentioned effects the engine should rather be operated at medium speeds but with open throttle. This requires an appropriate combination with the speed and power requirements of the driven machine.

APPLICATIONS OF BIOGAS ICE FOR ELECTRIC GENERATORS PLANNING OF A BIOGAS FACILITY

For potential biogas users, Claus Ruckest has made a test-list, which is presented in shortened form. Designer, advisor and manufacturer should also be consulted. The list suggests the following:

1. If there's an interest for biogas facility gathering of information is needed. Sources are food and agriculture departments, magazines and books.
2. Visit to biogas facility, which is similar to planned facility
3. Discussing of quantitative indicators related to gas and electric energy (mean values should be discussed)
4. Demands for cost participations
5. Examining of co-fermentation possibility
6. Contract for co-fermentation additives acquisition
7. Choice of type and size of biogas facility
8. Planning and authority licence
9. Acquiring of biogas facility manufacturers' offers
10. Building the biogas facility

THE BIOGAS ENGINE AS A MODULE INTEGRATED INTO AN ENERGY SYSTEM

The supply of mechanical, electric or thermal power from biogas is only feasible using a biogas engine. The installation of a biogas engine however requires an appropriate planning of the fuel production and also the consumption/operation procedures. This is a crucial exercise which can usually be-avoided when the power is purchased from an electric grid. As an engine in general does not supply energy, but rather transforms one form of energy, here biochemical, into another form, mechanical energy, its operation requires a source of energy on one side and a consumer of the energy on the other. The coordination of the energy source (biogas production plant), the transformer (engine) and the consumer (driven machine) is therefore of utmost importance for a technically and economically satisfactory performance of the whole system. The following parameters have an influence on the system's performance:

a) Technical Parameters

- Biogas production in the biogas plant under consideration of the plant's size, inputs and operation as well as the reliability of the gas supply system.
- Power demand of the driven equipment with regard to its anticipated fluctuation or the anticipated point of continuous operation.
- Demand of low and medium temperature heat from engine's waste heat (cogeneration).
- Daily schedule of operation with regard to biogas consumption, plant size and necessary gas storage capacity.
- Speed or speed range of the driven machine and the engine.
- Mode of control, manual or automatic.
- Local availability of engine service, spare parts, technical expertise and sufficiently competent operating personnel.
- Anticipated development of energy supply and demand in the future.

b) Economic Parameters

- Price of biogas plant cum ancillaries.
- Price of engine cum modification.
- Price of driven machine and energy distribution system (electrical wiring, water system, etc.) unless already existing.
- Operational cost of biogas system, i.e. plant, engine and driven machine.
- Cost of the system's service and maintenance.
- Capital costs (interest rates, pay back periods, etc.).
- Expected revenue from provision of selling energy or services, including the use of the engine's waste heat.
- Savings by the omission of cost for other fuels or forms of energy.
- Anticipated development of economic parameters (inflation, laws, regulations, fuel taxes, etc.).

c) Alternative Possibilities of Power Supply

- Electric motors under consideration of availability, reliability and price of electricity from another (e.g. public) supplier.
- Small hydropower in favourable areas for direct drive of machines or generation of electricity.
- Wind power in favourable areas under consideration of the schedule of power demand and the wind regime.
- Diesel, petrol, alcohol or LPG as engine fuels under consideration of availability, price and given infrastructure for a reliable supply.

To summarize, a biogas engine is only one module in a system and can only perform to satisfaction when all other components are well integrated. Furthermore the economic and boundary conditions, realistically assessed, have to be more favourable than for alternative solutions. Last but not least the actual situation exceeds the availability of technical equipment and expertise or other constraints can significantly influence the choice of the system and the planning process as a whole.

ECONOMIC AND OPERATIONAL CONSIDERATIONS

There are different basic situations out of which the use of biogas for the generation of mechanical or electric energy may be considered.

a) Biogas availability or potential

- A biogas plant already exists and the gas yield is larger than what is already consumed in other equipment or the yield could be increased.
- Organic matter is available and otherwise wasted; the boundary conditions allow for anaerobic digestion.
- Environmental laws enforce anaerobic treatment of organic waste from municipalities, food industries, distilleries, etc.

b) Demand for mechanical power

- Other fuels are practically not available.
- Other sources of energy or fuels are more expensive or their supply is unreliable.
- Having a fuel at one's own disposal is of specific advantage.

c) Possible revenue through selling mechanical power, electric power or related services to other customers (e.g. the public electricity supply company).

In all cases it is essential to combine the modes of the generation of the fuel and its consumption. While the biogas is produced in a continuous mode, the demand for power, hence fuel, is often discontinuous. Biogas, unlike liquid fuels, can be stored in larger quantities either in a compressed form requiring special efforts or in large, low pressure storage tanks. However, both ways are costly. This provides an incentive to avoid extensive storage through a well-balanced production and consumption of biogas.

One way of equalizing the demand profile is the continuous operation of the engine, hence continuous fuel consumption. Instead of operating a powerful machine and engine for a short period per day the same service can often be obtained by a smaller system operating for a longer period. A similar effect is reached by the operation of different equipment in a sequence rather than at one time, e.g. water is pumped overnight while grains are milled during the day. The smaller system not only requires lower investment itself, but it also requires smaller or no gas storage capacities. The planning of the operational schedule of the equipment has a considerable effect on the economics and feasibility of biogas engine projects.

In cases where biogas is used for electricity generation, the mode of operation, i.e. in an isolated grid or in parallel to an existing larger grid (e.g. public utility), further influences the power demand situation and the choice of the gen-set's power class.

INVESTMENT AND OPERATIONAL COST

Investment for the biogas engine system will differ from case to case, depending on what is actually required for completion of the system:

- biogas plant, gas storage,
- biogas piping and instrumentation,
- engine cum modification,
- driven machine cum transmission,
- civil works, i.e. foundations, sheds, fences, etc.,
- wiring, piping, switchgear.

Often the biogas plant already exists or is being built as a biological treatment plant for wastes, residues or other. It is therefore not part of the investment for the engine system. In other cases an engine cum driven machine is already there while a plant, its infrastructure and engine modification is needed.

The operational costs involve the manpower, service and maintenance of the system as mentioned earlier. Again, if for instance the operation of the plant is done and paid for under a different aspect, e.g. waste treatment, the "biogas fuel price" is lowered as it only needs to consider the efforts for gas preparation, e.g. piping, storage, measuring, etc. Further influence on the fuel price comes from the production rate of the biogas plant.

The establishment of a biogas fuel price (per m^3 or per kWh) is useful where a biogas engine competes against differently fuelled engines or electric power. Whatever the actual situation, biogas will never be a fuel absolutely "free of charge."

CHOICE OF ENGINE

An engine is mainly specified by its type and by its maximum (rated) power at its maximum speed (e.g. "Otto engine, 45 kW at 5200 1/min or rpm"). What this means is that it may well be operated at lower speeds and power output but not above the maximum data given. An operation at lower power and speed than the maximum will often be found more economic in terms of fuel consumption and engine life. When considering the purchase of an engine one should not confuse the maximum or rated performance as given in the technical specification of an engine with the optimum performance in economic terms. The engine's performance curves, i.e. power, torque and specific fuel consumption vs. speed, are much more useful in determining the point of operation and selecting an engine that will meet the driven machine's requirements while it operates at a high efficiency.

The determination of the main operational parameters of an engine, i.e. range of power and speed, is largely a function of the requirements of the driven machine. The choice of engine type, however, follows the availability, the market situation (price) for fuel, spares and service and some other operational parameters like the required type of control, fuel availability, etc.

BIOGAS FOR VEHICLES

The utilization of biogas in vehicles requires a method of compact storage to facilitate the independent movement of the vehicle for a reasonable time. Larger quantities of biogas can only be stored at small volumes under high pressure, e.g. 200 . . .300 bar, or purified as methane in a liquid form at cryogenic conditions, i.e. -161 °C and ambient pressure. The processing, storage and handling of compressed or liquefied biogas demand special and costly efforts. Compression is done in reciprocating gas compressors after filtering of H_2S. At a medium pressure of about l5 bar the CO_2 content can be "washed out" with water to reduce the final storage volume. Intermediate cooling and removal of the humidity in molecular sieve filters are essential as the storage containers should not be subjected to corrosion from inside. The storage cylinders, similar to oxygen cylinders known from gas welding units, can be used on the vehicle as "energy tank" and in larger numbers as refilling store. One cylinder of 50 l volume can store at a pressure of 200 bar approximately

- 15 m^3 un-purified biogas (CH_4 = 65% Vol.) with an energy equivalent of 98 kWh or diesel fuel, or
- 13 m^3 purified biogas (CH_4 = 95% Vol.) with an energy equivalent of 125 kWh or diesel fuel.

The storage volume thus required on the vehicle is still five times more than is required for diesel fuel. Purification of biogas to CH_4 increases the storage efficiency by 25 to 30% but involves an extra gas washing column in the process.

Purified biogas, i.e. methane, has different combustion features than biogas because of the lack of the CO_2 content. It combusts faster and at higher temperatures; this requires different adjustments of ignition timing. Dual fuel methane engines are prone to increased problems with injector nozzle overheating and have to operate on higher portions of diesel fuel (about 40%) to effect sufficient cooling of the jets. Liquefaction of biogas requires drying and purification to almost 100% CH_4 in one process and an additional cryogenic process to cool the CH_4 down to -161 °C where it condenses into its liquid form.

Storage is optimal at these conditions as the volume reduction is remarkable, i.e. 0.6 m^3n with an energy content of 6 kWh condense to one lifer of liquid with an energy equivalent of 0.61 diesel fuel. The required tank volume is only 1.7 times the volume needed for diesel fuel. This advantage is opposed by a more sophisticated multistage process, the handling of the liquid in specially designed cryo-tanks with vacuum insulation and the fact that for longer storage it has to be kept at its required low temperature in order to prevent evaporation. This requires additional energy and equipment. Data on the economic viability are not yet available. The use of biogas as a fuel for tractors on farms has been elaborately researched. The processing of the gas does not only require about 10% of the energy content of the gas, mainly for compression, but also involves considerable investment. The tractor itself needs to carry four gas cylinders at least for a reasonable movement radius. A 40-kW tractor can then operate for about six to seven hours at mixed/medium load. The modification of the tractor has to include a three-stage pressure reduction system as the fuel gas is fed to the mixer at low pressure, i.e. about 50 mbar. Modification into an Otto gas engine includes the risk of non-availability of the tractor at biogas shortage. It therefore needs LPG as spare fuel or another diesel tractor standby. Dual fuel tractor engines, on the other hand, are difficult to control, especially because of their frequent speed and load changes during operation in the field. Biogas for road service has become an issue in Brazil lately. It must however be seen in connection with the specific situation in this country. The main issue is to utilize the large natural gas resources for substitution of diesel fuel, which is scarce. Purified biogas is therefore integrated into a larger "methane program", for which the government may decide to give specific economic preferences because of energy-political reasons. The biogas will furthermore be obtained and processed in larger units, e.g. municipal sewage plants and sugar factories, which reduces the cost per m^3 considerably. With the current (political) price of fuel in industrialized countries the equivalent price for "vehicle biogas" is about two or three times higher than for diesel fuel. It is therefore presently not economic though technically feasible to use biogas in vehicles on a larger scale. The infrastructure for processing and filling however must also be developed accordingly.

CONCLUSION

Cattle dung is a resource. For better results, concerted efforts are needed to improve the biogas programme. Good work done by trained masons, technicians, NGOs, etc., should be recognized by organizing healthy competitions at the block and district level and awarding the best performing persons and organisations. Plant owners, using biogas and manure efficiently should also be awarded on an annual basis. Do-it-yourself manual on the operation and maintenance of biogas plants for plant owners, construction manuals for masons, manuals on laying gas distribution pipe line and operation of IC engines for technicians, biogas plant users' manual, etc. should be brought out in regional languages and widely distributed. The use of digested slurry in conjunction with chemical fertilizers should be encouraged to increase the fertilizer use efficiency. Further research data indicate that the use of biogas-slurry manure reduces the adverse affect of injudicious application of pesticides on soils. Therefore, to generate awareness among farmers, field demonstrations on the use of biogas-slurry manure should be organized. Also greater R&D efforts should be made to focus on diversified value added use of manure, e.g. for hardening of tissue cultured seedlings, abatement of soil-toxicity, as a source of micro-nutrients and root stimulant for fruit and vegetable crops, etc. Several private dairies possess large number of cattle heads and many-a-time face the problem of disposal or use of cattle dung in towns and cities. To overcome this problem, the biogas technology coupled with electricity generation should be promoted with focus on production and marketing of manure.

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