HYBRID PROPULSION SYSTEM BASED ON AN ICE FUELED BY METHANOL DISSOCIATION PRODUCTS - GENERAL CONCEPT

Dr L Tartakovsky, Dr Y Aleinikov, Dr V Fainberg, Dr A Garbar, Dr M Gutman,
Prof G Hetsroni, Dr Y Schindler and Prof Y Zvirin,
Technion - Israel Institute of Technology
Israel

98EL018

ABSTRACT

The paper presents a general concept of a hybrid propulsion system, based on an SI internal combustion engine fueled by methanol dissociation products (MDP). The proposed hybrid propulsion scheme is a series hybrid, which allows the engine to be operated in an on-off mode at constant optimal regime. The engine is fed by gaseous products of methanol dissociation (mainly hydrogen and carbon monoxide) emerging from an on-board catalytic reformer. The general scheme and base operation features of the propulsion system are described. The benefits that may be achieved by combining the well-known idea of on-board methanol dissociation with the hybrid vehicle concept are discussed. The proposed scheme is compared with those of systems operating on gasoline, liquid methanol, hydrogen and also with the multi-regime (not hybrid) engine fed by MDP.

1. INTRODUCTION

HYBRID VEHICLES. One of the main features of today's progress in the automotive industry is a transition from the concept of emissions control to the concept of emissions prevention. The most prominent example of this trend is the CARB requirements for Zero Emission Vehicle (ZEV), [1]. However, some of the ZEV components (battery, flywheel, super capacitor etc.), based on the present level of scientific knowledge and technological development have several significant shortcomings (such as low energy and power density, safety problems, high cost, etc.). These lead to low range, poor acceleration and high cost of the vehicle, which make the ZEV a rather unattractive option from the point of view of the consumers. Therefore, hybrid vehicles are now under consideration, because of the possibility to achieve high performance together with the "zero emission" option for city center driving, and low emission in inter-urban roads, [2 - 4].

There are two main types of a hybrid drive system used today in vehicles: so called parallel and series hybrid. In the former, an internal combustion engine (ICE) is mechanically connected to the vehicle's transmission and can supply the power to the vehicle wheels in parallel with an electric motor. This hybrid type may sometimes be preferable for dual-mode vehicles, [2], but it has some serious disadvantages, such as need for complex conventional transmission and a complex control system (compared to the series hybrid). The ICE operates in this type of hybrid as in a conventional vehicle, in a wide range of operational regimes, which leads to increase of pollutants emission and fuel consumption. In a series hybrid, the ICE is connected to a generator and the vehicle wheels are driven only by electric motor(s). In this case, there is no need for a complex vehicle transmission and an energy storage system may be used to average-out load variations, allowing the engine to operate at a constant regime with maximal possible efficiency. The main drawback of a series hybrid scheme is a possible reduction in the battery's service life because of a great number of charge-discharge cycles. However, it is clear that the design of a low emission and highly efficient system is much easier under these conditions, [5, 6].

ALTERNATIVE FUELS. Use of various alternative fuels (such as alcohols, natural gas, LPG, etc.) for hybrid propulsion is widely considered today as an additional possibility of emissions reduction. Among them, methanol is well known as a promising alternative fuel, mainly due to the potential of reducing engine exhaust emissions and considerations of supply security. It is available in many regions and can be efficiently and economically produced in large quantities from a variety of feedstocks, including natural gas, coal and biomass, [7, 8].

Some of the main drawbacks of liquid methanol as an automotive fuel are its relatively low heating value, leading to high volumetric fuel consumption, poor engine startability at low ambient temperatures, high corrosivity and a rise in aldehydes emissions, [7].

METHANOL DISSOCIATION is investigated today, because it is a promising hydrogen source for propulsion systems based on fuel cells, [9, 10], and its products can serve as an excellent hydrogen enriched gaseous fuel for an ICE, [11 - 16].

Methanol dissociates in the presence of a catalyst into hydrogen and carbon monoxide. The ideal reaction can be written as:

$CH_3OH \rightarrow 2H_2 + CO$ (1)

Some side reactions also occur during methanol dissociation, as outlined in the following equations, leading to the formation of small amounts of dimethyl ether (eq. 2,5), methyl formate (eq. 6), formaldehyde (eq. 7), etc. in the MDP.

$2CH_3OH \rightarrow (CH_3)_2O + H_2O$ (dehydration) (2)
$2CH_3OH \rightarrow CH_4 + 2H_2 + CO_2$ (methanation) (3)
$2CH_3OH \rightarrow CH_4 + CO + H_2 + H_2O$ (dehydration) (4)
$3CH_3OH \rightarrow (CH_3)_2O + CO_2 + 3H_2$ (decomposition) (5)
$2CH_3OH \rightarrow HCO_2CH_3 + 2H_2$ (dehydrogenation) (6)
$CH_3OH \rightarrow CH_2O + H_2$ (formaldehyde synthesis) (7)
$CH_3OH \rightarrow C + H_2 + H_2O$ (carbonation) (8)
$2CH_3OH \rightarrow C_2H_4 + 2H_2O$ (olefine synthesis) (9)

It is possible to diminish the contribution of these reactions to the final MDP composition by the appropriate choice of a catalytic material and optimization of the reformer's operation conditions.

Several catalysts for methanol decomposition into CO and H_2 have been proposed: palladium [18], Cu/Cr based catalysts [19], CuCl-KCl or CuCl-$ZnCl_2$-KCI catalysts on various supports [17], etc. The decomposition can be accomplished by passing vaporized methanol over a catalyst at temperatures above 300°C, [11 - 16]. Therefore, heat is needed to vaporize methanol and to drive the endothermic dissociation reaction. It may be supplied by waste heat recovery of the ICE exhaust gases. The schematic layout of a typical on-board methanol dissociation system which has been studied in previous research works [11 - 16, etc.], is shown in Figure 1. According to this scheme, the recovered waste exhaust heat is stored as a fuel energy. The lower heating value of the MDP is 23.97 MJ/kg, [15], compared to 19.94 MJ/kg of liquid methanol and 21.02 MJ/kg of methanol vapor. In other words, the MDP fuel has an about 20 and 14 percent higher heating value than liquid methanol and vaporized methanol. If the engine efficiency will be the same for all these fuels, a corresponding improvement in fuel economy would be expected for MDP compared to liquid methanol. There is also no doubt as to the possibility to obtain an effective transformation of methanol into hydrogen and carbon monoxide. The problem is: how to perform this under the conditions of a real transport engine? The results of published efforts to develop an on-board methanol dissociation system for a conventional motor vehicle, have shown a number of serious problems, mainly caused by the multi-regime nature of a conventional engine operation (these problems will be discussed in section 3 below), which lead to the gradual reduction of the automotive industries' interest in this promising idea. Nevertheless, using the concept of methanol dissociation for a low emission hybrid propulsion system seems to be a very attractive option, with a potential to renew the interest in on-board methanol dissociation.

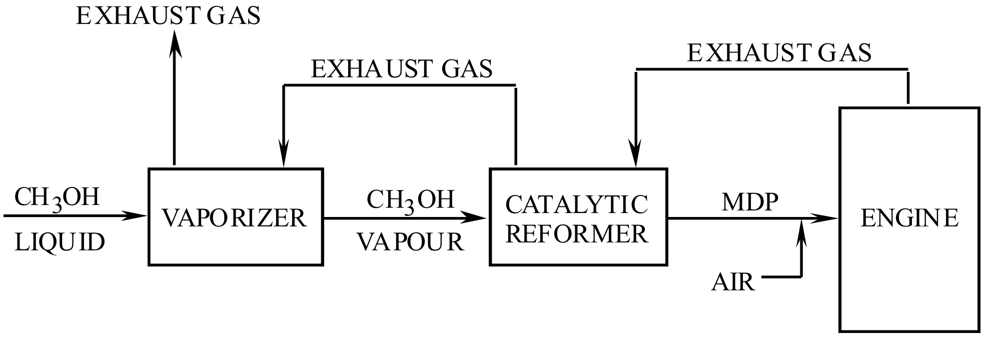

Figure 1. Scheme of on-board methanol dissociation system (based on [15])

2. THE BASIC IDEA

The idea is to develop a hybrid propulsion system based on an ICE fueled by methanol dissociation products. The hybrid concept is a series scheme: a vehicle driven by electric motors powered from a storage system of energy, supplied by charging from an electricity network or/and by an internal combustion engine through a generator. The ICE runs in an on-off mode, at an optimal operation point, fed by products of methanol dissociation, MDP, (mainly hydrogen and carbon monoxide) emerging from the on-board catalytic reformer.

Using the MDP as a fuel for an internal combustion engine make it possible to benefit from hydrogen-enriched gaseous fuel, to eliminate the known problems of on-board hydrogen storage and to reduce substantially expenses compared to the use of fuel cells. Using the scheme of series hybrid (see Figure 2) allows the engine to be operated in an on-off mode at constant, optimal regime. Excess energy produced by the engine at lower load driving conditions is accumulated by the energy storage system of the hybrid. The engine is automatically switched-off and only electric propulsion is used in the case of a full-charge state of the energy storage system.

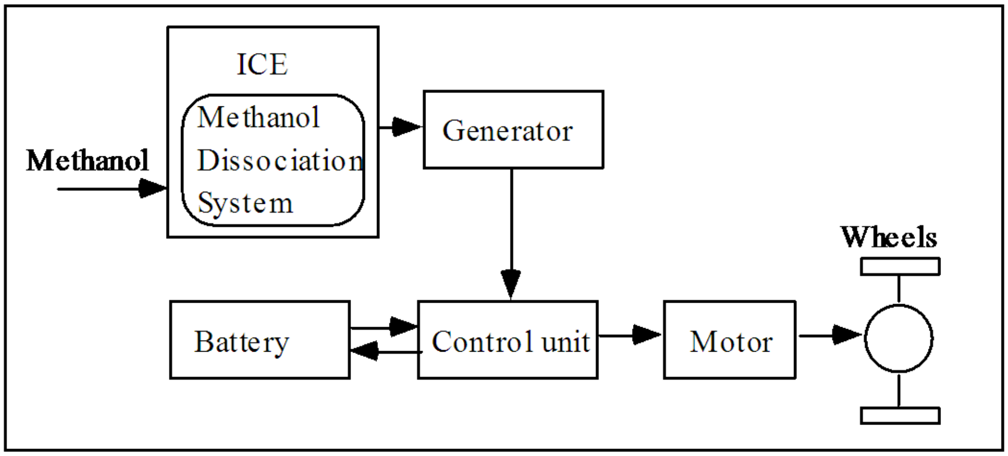

Figure 2. Scheme of the series hybrid propulsion system with on-board methanol dissociation

High hydrogen content (above 60% vol.) of the dissociated methanol allows much leaner combustion than liquid methanol or gasoline, resulting in a sharp reduction of NO_x formation and decrease in CO_2 and, of course, CO and HC emissions. Engine operation at the constant optimal regime contributes to additional significant rise in efficiency and reduction in pollutants emission.

3. COMPARATIVE ANALYSIS

Table 1 includes the results of a qualitative comparison of the proposed hybrid concept and some other fuel-vehicle systems. Performance parameters of a hybrid vehicle with a gasoline engine are taken as a base values for this comparison. As can be seen from Table 1, and as known from the technical literature, e.g. [7, 20], the main advantages of using liquid methanol as an alternative fuel are the possibility to improve engine efficiency, to reduce emissions of some pollutants and, of course, to contribute to the solution of the problem of supply security. Improvement in engine efficiency can be achieved with methanol due to its excellent antiknock performance, lower flame temperature and luminosity (leading to lower heat losses) and high latent heat of vaporization, which allows the achievement of higher volumetric efficiency. Using the liquid methanol as a fuel enables reduction of benzene, 1,3 butadiene and OMHCE (organic matter hydrocarbon equivalent) emissions together with a lower photochemical reactivity of emitted pollutants, [7]. However it leads to rise in NMOG (non-methane organic gases) and aldehyde emissions (this is the reason for the ± mark in the appropriate cell of Table 1). Additional shortcomings of the liquid methanol as a motor fuel which are reflected in Table 1 and were also briefly mentioned in the Introduction, are:

- low energy content compared to gasoline and therefore higher volumetric fuel consumption;
- low vapor pressure and high latent heat of vaporization, leading to the poor cold starting and warm-up performance;
- high corrosivity and washing-away of lubricant leading to engine durability problems.

Table 1. Qualitative assessment of various fuel-vehicle systems.

Parameter	Gasoline ICE for hybrid vehicle	Methanol ICE for hybrid vehicle	Hydrogen ICE for hybrid vehicle	MDP ICE for motor vehicle	MDP ICE for hybrid vehicle
Tailpipe emissions	0	+ –	+++	++ –	++
Energy consumpt.	0	+	++	++	+++
Cold startability	0	– –	+	– –	0 +
Engine durability	0	–	0	–	0
On-board fuel storage	0	0	– – –	0	0
Fuel cost	0	0 +	– – –	0 +	0 +

Key:

+ + +	the best	0	taken as a base value or close to the base value
+ +	signficantly better		
+	better	–	worse
0 +	close or slightly better	– –	significantly worse
		– – –	the worst

Hydrogen is considered as a very promising alternative motor fuel in the long-term perspective. It enables sharp reduction in pollutants emission and meeting the CARB ULEV standards relatively easily, [3, 21]. Data and theoretical considerations show that optimized hydrogen ICE are 15 - 25% more efficient than gasoline engines, [21]. But, as can be seen from Table 1, storage of hydrogen on-board a vehicle and cost of its production remain a major technological challenge. The cost of hydrogen produced by stripping it from natural gas (the least expensive large scale process) is 1.5 - 9 times higher than that of gasoline, [21]. Production of H_2 by electrolysis of water is also considered as a potential long-term option, but this method is extremely expensive with today's technology, [7]. The problem of hydrogen storage on-board a vehicle is directly related to its physical properties: extremely low boiling point (- 253 ^oC) and very low volumetric energy content. The main methods of on-board H_2 storage considered today are: storage of compressed H_2 at pressure of about 300 bar, storage of liquefied H_2 in cryogenic tanks and H_2 storage in metal hydrides. Each of these methods has serious drawbacks, such as high weight penalties, safety risks, high cost, etc.

Using the MDP as an automotive fuel allows, as mentioned above, consolidation of the benefits of liquid methanol cost and on-board storage with engine feeding by a gaseous non corrosive hydrogen enriched fuel. But implementation of an MDP ICE in a conventional motor vehicle leads to the need of a multi-regime engine with all the requirements from the fuel and control systems ensuing therefrom. A catalytic reformer is needed to operate efficiently in a wide range of methanol flow rates and exhaust gases temperatures (as a result of engine load and speed changes). There is a requirement and a serious problem to ensure engine cold start and warm-up, because at low temperatures the catalytic reformer will not operate efficiently (reformer lighting off). The requirement to address any momentary change in engine load leads to a serious complication of the fuel and control systems. As follows from the published data, e.g. [11 - 16], these problems have not been fully solved. In order to enable satisfactory engine operation in the whole range of working regimes, different amounts of methanol are usually added to the MDP fuel. This leads to problems which are typical for liquid methanol: high aldehydes emissions, increased wear, poor cold startability, etc. These main shortcomings, together with the complexity of the required fuel and control systems, substantially reduced the attractivity of the MDP ICE idea.

The proposed system opens new possibilities to achieve great advantages of the well-known idea of on-board methanol dissociation, by combining it with the hybrid vehicle concept. The benefits follow from the availability of an energy storage device and the operation of the ICE at optimal steady-state regime, and may lead to the elimination of current shortcomings of multi-regime fuel systems with methanol dissociation. Among the problems which may be eliminated, or at least minimized, are: undesirable chemical reactions in the catalytic reformer which usually lead to the reduction of hydrogen yield, rise of soot formation with subsequent increase of radiation heat losses, etc., [11, 13] (the hybrid reformer operates at an optimized steady-state regime); cold start and warm-up problems (the reformer may be electrically preheated from an energy storage device); problems which follow from the requirement to address any momentary change of needed fuel amount, taking into account the residence time of the fuel in the catalytic reactor, etc. As a result of these advantages, the fuel and control systems can be made much simpler, effective and less expensive and, of course, better fuel economy may be achieved.

4. SUMMARY

A hybrid propulsion system based on an ICE fueled by methanol dissociation products is proposed. Using the scheme of series hybrid allows the engine to be operated in an on-off mode at constant optimal regime. Excess energy produced by the engine at lower load driving conditions is accumulated by the energy storage system of the hybrid. The proposed system allows great advantages of the on-board methanol dissociation to be achieved by combining this idea with the hybrid vehicle concept. The benefits of the proposed system follow from the availability of an energy storage device and the operation of the ICE at optimal constant regime.

Among the problems typical for MDP multi-regime engine which may be eliminated, or at least minimized, are:

- undesirable chemical reactions in the catalytic reformer;
- cold start and warm-up problems;
- need to address any momentary variation in engine load by the appropriate change in the fuel supply.

By using the proposed system, it is possible to overcome the main shortcomings of liquid methanol and hydrogen fueled engines.

ACKNOWLEDGEMENT

This research was supported by the Henry Ford II Transportation Research Fund and the Fund for the Promotion of Research at the Technion. The authors are grateful for both Funds for their support.

5. REFERENCES

1. Motor Vehicle Emission Regulations and Fuel Specifications in Europe and the United States. 1995 Update. CONCAWE Report 5/95, Brussels, December 1995.
2. D. Sperling, Future Drive, Electric Vehicles and Sustainable Transportation. Island Press, USA, 1995.
3. R.Q. Riley, Alternative Cars in the 21st Century. A New Personal Transportation Paradigm. Published by SAE, USA, 1994.
4. R.D. King, K.B. Haefner, L. Salasoo and R.A. Koegl, Hybrid Electric Transit Bus. IEEE Spectrum, pp. 26-31, July 1995.
5. K. White, Should Government and Industry Work Together to Develop Technology: A Case Study of the United States Advanced Battery Consortium (USABC). SAE Paper 961026, 1996.
6. K.L. Heitner, Energy Storage Requirements and Optimization of Sustaining Power Source for Hybrid Vehicles. Paper AIAA-94-3918-CP, 1994.
7. Y. Zvirin, M. Gutman and L. Tartakovsky, Fuel Effects on Emissions. Chapter 14, Handbook of Air Pollution from Internal Combustion Engines: Pollutants Formation and Control, edited by E. Sher, Academic Press, pp. 548 - 651, 1998.

8. A. Brandberg, M. Ekelund, A. Johansson and A. Roth, The Life of Fuels: Motor Fuels from Source to End Use. Ecotraffic AB, Stockholm, March 1992.
9. R. Krauss, J. Friedrich and K.E. Noreikat, Fuel Cell Cars - Preparation of a Quantitative Description by Experiment and in Theory. Paper 97 EL 075, Proc. 30th ISATA, Florence, Italy, June 1997.
10. P. Grimes, Fuel Cell Fuels. Paper 97 EL 089, Proc. 30th ISATA, Florence, Italy, June 1997.
11. M.E. Karpuk, S.W. Cowley and M. Ratcliff, Design and Testing of a Dissociated Methanol Vehicle. Proc. VIII Int. Symp. on Alcohol Fuels, pp. 655-661, Tokyo, November 1988.
12. Y. Aleinikov and S.A. Chizhov, Effects of Adding Methanol Decomposition Products on the Performance of a Diesel Engine. Trans. of the Moscow Inst. of Transportation (MIIT), No. 748, pp. 33-37, 1985.
13. Y. Aleinikov, Improvement of the Performance and Reduction of Emissions of Locomotive Diesel Engines by Using Synthetic Alcohols and their Decomposition Products. Thesis for Ph.D. scientific degree, MIIT, Moscow, 1984.
14. K. Korematsu, T. Saika and K. Itoh, Optimized Operating Region of Dual Fueled Diesel Engine with Dissociated Methanol and Gas Oil. Proc. VIII Int. Symp. on Alcohol Fuels, pp. 649-654, Tokyo, November 1988.
15. N.D. Brinkman and R.F. Stebar, Comparison of Methanol and Dissociated Methanol Illustrating Effects of Fuel Properties on Engine Efficiency - Experiments and Thermodynamic Analyses. SAE Paper 850217, 1985.
16. A. Konig, K.W. Ellinger and K. Korbel, Engine Operation on Partially Dissociated Methanol. SAE Paper 850573, 1985.
17. A. Schmitz, D. Eyman and K. Gloer, Highly Active Methanol Dissociation Catalysts Derived from Supported Molten Salts. Energy and Fuel, vol. 8, pp. 729-740, 1994.
18. J.-J. Chen, et al., Spectroscopic Studies of Methanol Decomposition. Surface Science, vol. 328, pp. 248-262, 1995.
19. W.-H. Cheng, Deactivation and Regeneration of Cu/Cr Based Methanol Decomposition Catalysts. Appl. Catal. B., vol. 7, pp. 127-136, 1995.
20. K. Owen and T. Coley, Automotive Fuels Reference Book, SAE, 1995.
21. C.A. Kukkonen and M. Shelef, Hydrogen as an Alternative Automotive Fuel: 1993 Update. SAE Paper 940766, 1994.