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ZEMPES (Zero Emissions Membrane Piston Engine System)

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ABSTRACT

The scheme of piston engine system for vehicles without exhaust of carbon containing combustion gases is presented. It comprises a piston engine with carburettor , using as oxidizer the "artificial air"(mixture of oxygen and carbon dioxide), a dense ceramic membrane, to separate oxygen from air, a turbocompressor to feed membrane by air and utilize some waste heat, a water separator to inject combustion born water in air flow before or after turbine and a compressor of carbon dioxide with associated radiator to liquefy carbon dioxide with dissolved contaminants , store it onboard and discharge in a tank at the fuel filling station.

GENERAL OBJECTIVE

The IPCC expressed the global warming menace in such a wordings: *All projections produce rate of warming greater than those experienced in the last 10 000 years, with a more vigorous hydrological cycle potentially affecting the rate and scale of various extreme events, such as drought, flood and rainfall (Greenhouse Issues-May 1996).* In 2002 Summer many people in Europe really suffered from the two last events. The correctness of the forecast of IPCC is evident now.

Preventing of the global warming urges the drastic engineering measures to curb the emission of carbon dioxide. In other words, to implement the zero emission technology.
The well established term "Zero Emission Technology" described in recent report of International Energy Agency /1/ heavily relates to big concentrated sources of emissions, like power plants or refineries. There exists, however, a source of pollution much more dangerous in view of either lung diseases or greenhouse effect, it is the combustion products of about half a billion of cars and other vehicles, using piston engines.

Major combustion product of piston engine, carbon dioxide, in principle can not be decomposed at the end of the pipe due to energy conservation Law. To cope with the problem of CO2 emission the two approaches are underway: a)Increase efficiency, b) Shift to other, non-carbon, fuels like hydrogen and electricity.

After decades of research, consumption of billion-scale funding and big fuss in media the practical result is still invisible. The efficiency increase in vehicle engine had reached a limit about 30%, its increase even with fuel cells on the hydrogen from reformulated fuel might be minor, it can not prevent CO2 emission. The use of hydrogen as fuel or electricity leads to very large energy storage onboard, which exceeds the vehicle size. To have enough energy density the hydrogen should be compressed in a fuel tank up to 700 bar !Shift to these energy carriers leads to the total change of existing infrastructure, filling stations, fuel supply systems e t.c. with insurmountable cost.

. That is why in recent decade the direct approach has been discussed: zero-emission engine on the ordinary hydrocarbon fuel. One of the first offers of such engines, not piston but turbine one, comprises a fuel combustion in the mixture of oxygen and steam/2/. High pressure (240 bar) and temperature (1000 C) steam with CO2 expands in a turbine to 0.5 bar, then is condensed and returned to combustor. CO2 is deflected from water, compressed, cooled and stored onboard in the empty space of used fuel in a special fuel tank with a sliding baffle. Many years after this scheme has been patented/3/ and used in USA for a big project.

The main problem of such schemes is the oxygen supply. The mature technology of cryogenic air separation is good for steady-state units, but incompatible with transport requirements of small size and vibration protection. To solve this problem the use of a capsule with solid oxygen (oxygen ice) by 50 K has been proposed in 1994/4/. A well thermally insulated capsule of 1 m length and 0.3 m dia contains sublimating oxygen up to two weeks. In two days one may use it for engine, changing the capsule together with refuelling and CO_2 discharging in a station's tank. This offer attracted no attention in practice.

The real breakthrough in the field of oxygen separation is the dense ceramic membrane technology. Such membranes are based on the discovered by W.Nernst in 1899 property of some heated ceramic oxides to transfer pure oxygen from oxygen-rich flow of air to oxygen-lean other gases, which may sweep the penetrated oxygen. The selectivity of such membranes is 100% and permeability is about 1 g O_2/sq.m.sec./5-7/ It is enough for proposed system.

There are many known attempts to use membrane separation for oxygen production in turbine units of zero emission power plant like ZEITMOP/8/ or AZEP/9/ projects. However there are still unknown schemes of the use of membranes for oxidation in piston engines. **The objective of the paper is to develop energy efficient system for ordinary piston engines using ordinary hydrocarbon fuels without any emission of carbon dioxide and other contaminants.**

SCHEMATICS OF THE PROPOSED SYSTEM

We begin with simplified carburettor engine schematics (Fig.1).

Air enters the air compressor in the point 1, is compressed , heated in a heat exchanger from 2 to 3 and enters the Ion Transport Membrane Reactor. Here about 60% of oxygen from air is transferred through membrane wall to the permeate side, where oxygen is swept by the flow of combustion products CO_2+H_2O. The water, previously separated from gaseous CO_2, is injected into the flow of air to increase the turbine power (points 4-5). After expansion air and steam are discharged into atmosphere absolutely harmless.

Flue gases from piston engine, enriched by oxygen, first are cooled in ITM reactor (18-19) then in the heat exchanger (19-20) and finally are cooled in a radiator with a fan. By ambient temperature the water is liquid, whereas CO_2 is gaseous, they are easily separated. Dry mixture of CO_2 /O_2 enters a carburettor, where atomized fuel is injected, the combustible mixture (9) enters the suction valve of piston engine. After ordinary processes of compression, ignition, expansion with power production and discharge, in the point 16 are CO_2, H_2O and some contaminants. Major part of flue gases is directed to permeate side of ITMR to sweep oxygen, whereas a minor part, some percents, is deflected out of the cycle in point 17, then compressed to about 70 bar and is cooled in a radiator to liquefy CO_2. It is then stored in liquid form in a fuel/CO_2 tank with a sliding baffle (or in a separate tank) onboard to be discharged at a fuel filling station.

The benefit of the scheme is the use of turbocompressor not only to provide ITMR by air, but also to use heat from flue gases to produce additional power. It might be referred to as the Otto-Brayton power cycle.

For starting from the cold state the turbocompressor runs by a motor from accumulator and some fuel is combusted in the feed side of ITMR, heating the membranes. CO_2 emission ends with the end of start.

ITM REACTOR

Such reactor looks like an ordinary shell-and-tube heat exchanger, where tubes are made of dense ceramic membrane material. The process of transfer of oxygen molecules through some heated ceramic oxides, discovered by W.Nernst in 1899, is extensively investigated in many Laboratories, the most important results for ZEMPE were obtained under leadership of Dr. H.Bouwmeester in the University of Twente, the Netherlands /5-7/.

By recommended temperatures (800-900 C) and pressures (air 5bar ,sweeping flow 1-2 bar), the oxygen flux density reaches j=1 g/sq.m.sec. This reliable averaged figure is used to evaluate the size of ITMR.

The typical power output of a car engine is about 60 kW. Assuming the thermal efficiency is 30 %, the heat flow required is 200 kW. If one tube has a diameter of 0.02 m and a length of 0.5 m, the heat transfer surface, F, is 0.0314 m^2. The energy flow through one tube is FjH = $0.0314\times0.001\times12.5.10^6$ = 0.39 kW by H= 12.5 MJ/kgO2. For 200 kW of heat flow, 200/0.39 = 513 tubes are needed, or 23 tubes along a side of square cross-section. If there are 0.03 m between the centers of the tubes, the length of the side of the square is 0.7 m and the total active volume of the ITM combustor is $0.7\times0.7\times0.5$ m^3 or 0.25 m^3. The size of the turbine and the compressor depends upon the air flow rate. By rotation speed about 1000 r/sec the size of both is negligibly small. The volume of a piston engine of 60 kW is about 0.4 cub.m . The total volume of the ZEMPE system (without CO2 tank) is about 0.7 cub.m which seems to be admissible for a 60-80 kW power.

CALCULATION OF MASS AND ENERGY BALANCE

The feasibility of the ZEMPES is demonstrated by the calculated mass and energy balances in all the node points of the scheme (Fig.2), which for the presented calculations is a little changed from the principal scheme of Fig.1 by addition a low pressure turbine T2, compressor C2 and radiators. Here is the Table 1 with parameters in node points.

Point	1	2	3	4	5	6	7	9	10	11
Subst.	Air	air	air	d.air	d.air	d.air	d.air+H2O		CO2+H2O	
G,kg/s	0.161	0.161	0.161	0.1409	0.1409	0.1409	0.1495	0.1425	0.1425	0.1425
T, K	293	504.8	1193	1193	872	387.4	379.7	1282	590.2	554.4
P, bar	1.013	5.07	5.05	5.05	1.03	1.02	1.01	1.61	1.59	1.03
H,kJ/kg	286.4	501.6	1248	1248	891.4	381.8	392.0	1468	632.9	583.2
W, kW	46.14	80.8	201.1	175.9	125.6	53.8	58.6	209.2	88.9	83.1

13	14	15	16	17	18	19	20	21	30	31	32
CO2 +H2O	H2O	CO2	CO2	CO2	CO2	CO2+O2		CO2+O2+f	CO2	CO2	CO2
0.1425	0.0085	0.134	0.134	0.134	0.114	0.1367		0.143	0.01973	0.01973	0.01973
313	313	313	346	313	313	451	313	313	313	676	313
1.02	1.02	1.02	1.58	1.56	1.55	1.55	1.54	1.52	1.56	58.4	58.4
320	573.2	303.8	337.3	303.7	304.4	438.3	299.2	312.6	304.1	684.2	304.1
45.6	4.9	40.7	45.2	40.7	34.7	59.9	40.9	44.7	6.0	13.5	6.0

The calculated power of some constituents of the system and its efficiency:
Turbines power, kW
T1 = 50.31, T2 = 5.74, Total = 56.05
Compressors power, kW
C1 = 34.68 C2= 4.53 C3 = 7.53, Total = 46.73
Piston engine indicator power = 94.52, its effective power = 78.49
Friction losses 3.92
Radiators fan power 8.9
Fuel energy input 280.33
Fuel consumption 22.8 kg/hour
Specific fuel consumption 290.4 g/kWh
System efficiency 28 %

The figures (volume of 0.7 cub.m and efficiency of 28 % by power of 78 kW) are similar to that of ordinary piston engines. It shows the feasibility of a ZERO EMISSION CAR ON ORDINARY FUEL.

FIGURE CAPTIONS

Fig.1. Principal scheme of the ZEMPES

Fig.2 Extended scheme for mass and energy balance calculations.

CONCLUSION

Results of preliminary calculations of the ZEMPES are encouraging. It is worth of further elaboration, optimization and intensive membrane tubes testing. Authors are working on the use not only dense membranes, but porous ones either.

REFERENCES

1.IEA Zero Emissions Technology Status Report, 2002, www.iea.org/impagr/zets/status/0202tsr.pdf

2.Yantovski E. The thermodynamics of fuel-fired power plants without exhaust gases. Proc. World Clean Energy Conf. CMDC, Geneva 4-7 Nov.1991, pp575-591.

3.Viteri F et al, Hydrocarbon combustion power generation system with CO2 sequestration, USPat 6,170,264 B1, Jan.9, 2001.
Clean air engines for transportation and other power applications. USPat6,247,316, June 19,2001.

4. Yantovski E. Energy and Exergy Currents. NOVA Sci Publ. New York, 1994.

5. Bouwmeester H., Burggraaf A. Dense ceramic membranes for oxygen separation. Ch-14, in the CRC Handbook of Solid State Electrochemistry, CRC Press, Boca Raton, 1996.

6. ten Elshof J.E. Dense inorganic Membranes. Ph.D. thesis, Uni of Twente, Enschede,1997.

7. van der Haar M, Mixed-conducting perovskite membranes for oxygen separation, Ph.D. thesis, Uni of Twente, Enschede, 2001.

8. Yantovski E., Gorski J., Smyth B.,ten Elshof J. ZEITMOP cycle (Zero Emission Ion Transport Membrane Oxygen Power) Proc.ECOS 2002, Berlin, 2-5 July 2002,pp 1153-1160

9. Griffin T. et al. CO2 control technologies :ALSTOM power approach. GHGT-6, Kyoto,1-4 Oct.2002, paper L3-2.

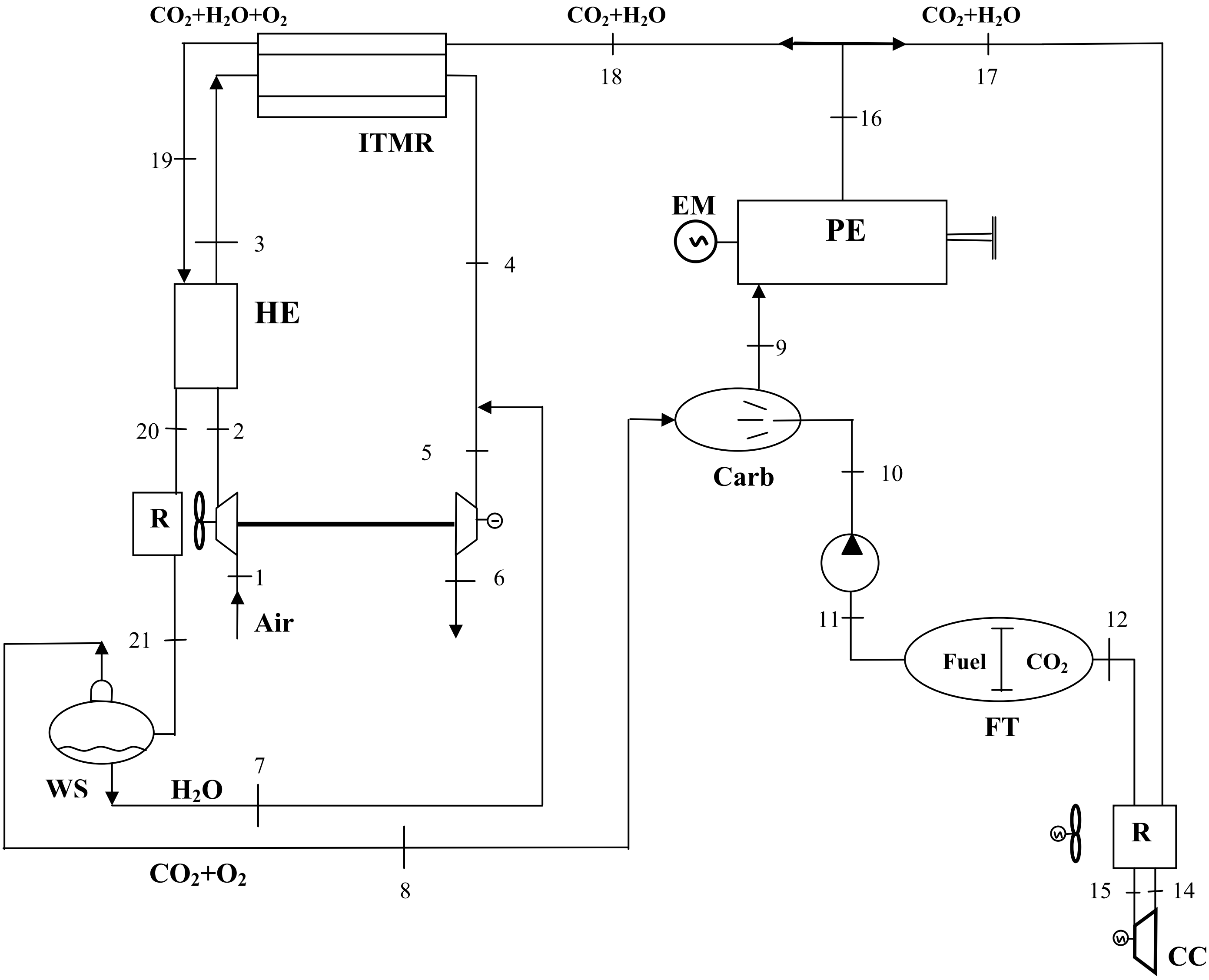

Fig.1. Schematics of the ZEMPES

TC=Air turbocompressor, HE=Heat Exchanger, R=Radiator-cooler,
WS=Water separator, FT=Fuel/CO_2 tank with sliding baffle,
PE=Piston engine, Carb=Carburettor, ITMR=Ion transport membrane reactor,
CC=CO_2 compressor, EM=Electrical machine.

Fig.2. Extended scheme for mass and energy balance calculations.(Dotted line to the entrance
of air compressor C1 shows an optional combustion-born water injection.)
Legend: C1=air compressor, C2,C3=CO_2 compressors; T1=air turbine; T2=CO_2 turbine,
R1, R2, R3, R4 = radiators with air cooling; OM=piston engine; HE=heat