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Zero emissions turbodiesel with membrane reactor (ZEMPES-turbo project)

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Abstract

The ZEMPES (Zero Emissions Membrane Piston Engine System) is using ordinary fuel and ordinary piston engines. The possibility to increase the fuel charge in cylinder due to enrichment of combustible mixture by oxygen and fuel in a lean burn diesel engine is examined. Such enrichment is possible by oxygen separation onboard in the ITMR (Ion Transport Membrane Reactor) without supercharger.

The excess of oxygen is used in an afterburner on gasoline before depleted air turbine. This turbine gives more power than piston engine.
For the numerical data demonstration the diesel Ford-425 as a prototype is selected.
The schematics of the system and tables of calculated efficiency and power versus the oxygen fraction in mixture O2+CO2 within the limits 0.209 – 0.4 are given. The dimensions of ITMR and high temperature heat exchanger are guessed. Their mass onboard is 193 + 50 kg.
The effective power of turbodiesel is increased from 52 up to 210 kW, turbocompressor gives 146 kW by oxygen fraction 0.4 (instead of 0.209 in air) and efficiency increase is from 0.35 in prototyp diesel up to 0.48 in turbodiesel with zero emissions.
Keywords: zero emission, carbon capture, membrane oxygen reactor, ceramic recuperator.

Introduction

The editor's paper "Up Front" in Power Engineering international Jan/Feb 2007. Senior Editor Heather Johnston asks "Is CCS ready for action ?" (CCS = Carbon Capture and Storage). She adds : people "mentioned that the idea of CCS being discussed at a mainstreem event such as POWER-GEN International would have been inconceivable as little as a one or two years ago. In the next issue of PEi she indicated:" Hunton Energy, a Texas based independent power producer, announced its intention to build $2.4 billion IGCC plant that will capture and sequester CO2". World Energy Council [1] includes in policy changes"implemented quickly within the electricity sector…carbon capture and storage (CCS) for power generation…"

Looking at the modern flood of papers on CCS we should remember the first proposal by C.Marchetti in 1977 and the documented history of engineering activity [5]. We see in the 5 Annual Conferences in the States and 6 International Conferences on Greenhouse Gas Control technologies the definitely positive ansver to the Johnston's question.

However **the fuel-fired power plants is only one culprit of carbon emissions. Even more dangerous is another one, the world fleet of vehicles**. The carbon capture on vehicles is more difficult due to volume and weight restrictions, but the principles of capture onboard are similar to that of power plant. Thinking on piston engines we may try to develop small power plants with cogeneration of heat for district heating to use it in densely populated urban areas as they are zero-emissions.

Concerted efforts of innumerous companies and labs directed to hydrogen cars and fuel cells for clean propulsion systems with spending of huge money are continuing. But still neither of hundreds of experimental cars reveals an ability to store enough energy onboard, comparable to a gasoline or compressed natural gas.

. In general our personal point of view is :**pollution is a violation of the main human right – to breathe. It is to be banned irrelevant to the greenhouse effect and global warming,** which are subjects of the greatest scientific controversy of modern time.

The reality of global warming now seems to be out of controversies. It definitely exists. Not only perfect measurements but also melting of polar ice and other evident events reveal the temperature increase. It is now clear what the problem is. Controversial remains an answer to the question what the solution should be, which in turn is splitted into the two questions 1) Who is responsible? 2) What should be done ?

The most authoritative in the 1)is Intergovernment Panel of Climate Change(IPCC) which issues Reports. In the recent one IPCC stated that climatic changes seen around the world are "very likely" to have a human cause.By "very likely" the IPCC means greater than 90% probability. At the launch of the recent Fourth Assessment reports the IPCC chairman Dr Rajendra Pachauri said: " If you see the extent to which human activities are influencing the climate system, the options for mitigating greenhouse gas emissions appear in a different light, because you can see what the costs of inaction are".

The accuracy of IPCC forecasts is seen from the following. In 2001 report was forecasted the temperature increase in 5 years as 0.15 – 0.35 C. Actually measured is 0.33 C, very near to the top of IPCC range.

Present paper is aimed at answering the 2) question and overthrowing the inaction in the ZEMPES demonstration. Converting vehicles fleet in zero emissions operation does not need the change of fuel supply infrastructure or engines. The gaseous emission is converted onboard into liquid, which is discharged on fuelling stations and sequestered in depth.
In view of large amount of papers, describing many cycles **of turbine power** units for power plants still there exists no description of such cycles **for piston engines** exept our previous papers.

Turbodiesel schematics and working process.

In order of the soonest demonstration just the diesel engine is selected because it is the working horse of american economics with very dirty emissions. In contrast to a popular slogan of proponents of fuel cell "New diesels will help bridge the gap to future fuel-cell vehicles"/6/, which needs the sulfur-free costly fuel, in ZEMPES the sulfur oxides would be dissolved in liquid carbon dioxide and stored underground together. That's why the large sulfur removal units and exhaust treatment systems with urea tanks and ammonia absorbers are not needed. The crucial thing: **all that cumbersome systems admit the carbon dioxide emission,** they can prevent the poisonous gases and particulate matter emission only, whereas ZEMPES prevents all the combustion-born emissions

Schematics is similar to previous ZEMPES versions[2,3,4]. The new element is the afterburner.

In turbodiesel there are three sources of thermal energy which might be converted into power:

1) fuel combustion in cylinder
2) fuel combustion in the afterburner
3) hot flue gases

The crucial figure is efficiency of turbodiesel. It is defined as the ratio of effective mechanical power (of piston engine + turbine) to the thermal energy of the both fuel flows. The thermal energy of flue gases originated from the same fuels . It should be used in the turbine to maximize efficiency.

In this paper only steady-state operation is considered. Any transient regimes still are out of discussion. For that matter should be known the thermal inertia of ITM reactor. In starting regimes probably would be first switched-on diesel with emission to atmosphere (admitted for the short time), then attached the turbocompressor and membrane reactor, which should be heated up to 900 C.

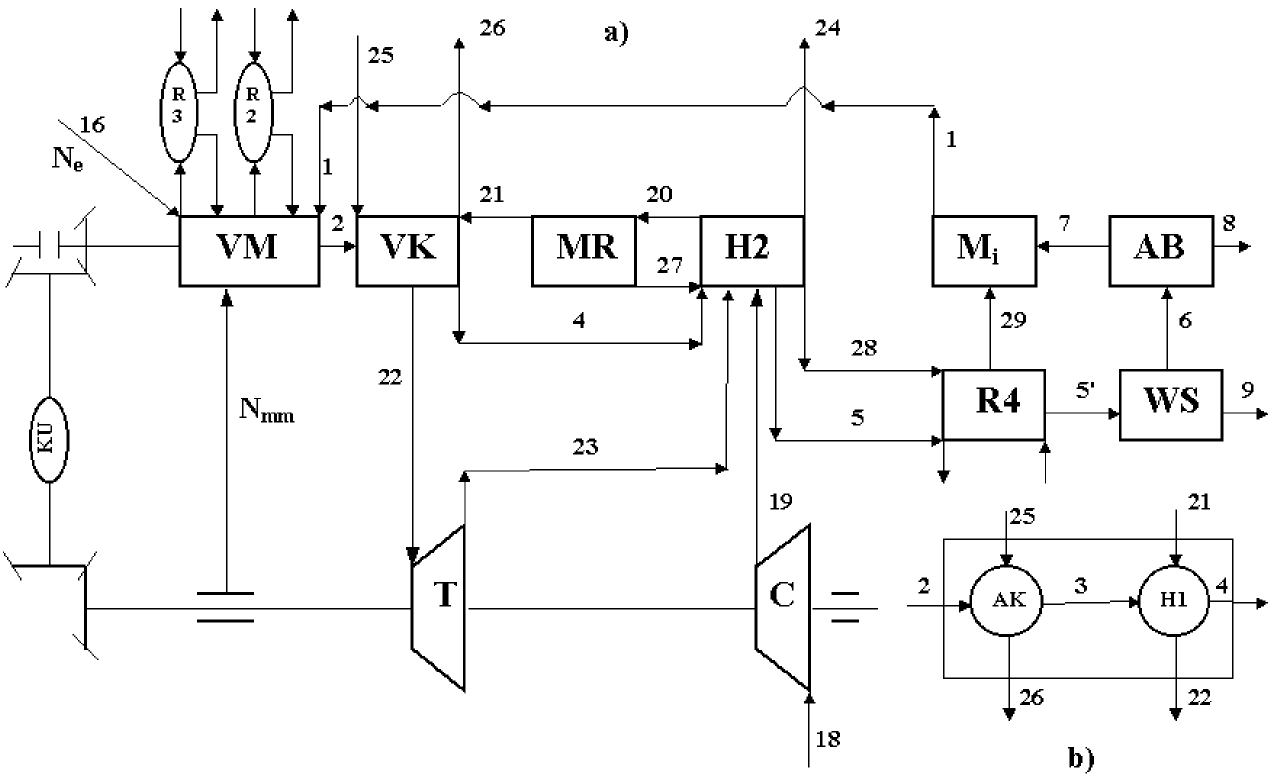


Fig.1. Schematics of turbodiesel.

R2 and R3 = oil and water radiators,VM = diesel piston engine; VK = afterburner, which consists of a combustor AK and heat exchanger H1, see scheme b); MR = membrane reactor for oxygen separation; H2 = multipurpose heat exchanger; Mi = mixer; AB = gas splitter; WS = water separator; R4 = cooler; Nmm = heat flow of mechanical losses in turbocompressor; KU = clutch, T = turbine; C = compressor

Working process consists of the two well known cycles: closed Diesel cycle 1-2-4-5-6-7-1 and open Brayton cycle 18-19-20-21-22-23-24. Let us start from Diesel cycle. To the suction is going the mixture of oxygen and carbon dioxide (artificial air, where nitrogen is replaced by carbon dioxide). After compression is injected diesel fuel. Expansion gives power, then displacement of much oxygen contained gases drives them into afterburner VK. Here almost all oxygen in combustor is used to burn the additional fuel (gasoline) and to heat air before the turbine.

After AK amount of oxygen is nil and flows in node points 3,4,5 are identical. After cooling the water is liquid but CO2 is gaseous, they are separated in WS, water is deflected and might be used elsewhere or to increase of turbine power. Almost dry CO2 is splitted in AB. Minor part, exactly equal to combustion born CO2, is liquified onboard by cooling, compression and more cooling and remains onboard under pressure about 100 bar to be discharged in a central tank at a fuel filling station. Major part of CO2 is going back to be mixed with oxygen and to form artificial air as an oxydizer in diesel cycle.

Open (Brayton)cycle started from ambient air in 18. After filter and compressor it is heated in H2 and enters membrane reactor MR, where about 60% of oxygen is penetrated through membrane wall into the CO2 flow. The rest of air is heated in afterburner and expands in turbine T giving additional power through reductor before KU. Reductor is essencial as the piston engine shaft rotates by 4000 r/min whereas turbocompressor shaft frequency is about 60 000 r/min. The depleted air after turbine is absolutely harmless, it contains no combustion products.

Membrane reactor

Well known cryogenic technology to separate air seems to be incompatible with any vehicle application due to large size of destillation columnes and vibration on a road. Other methods of separation by membranes might be divided by cold membranes (Pressure Swing Adsorbtion using, for example, the zeolite) and hot membranes using ion transport through dense wall by oxygen pressure difference. Membrane reactors might withstand inertial forces in vehicles. We have selected for ZEMPES the hot membranes due to possibility of the use air supply system as the bottoming Brayton cycle for efficiency increase.

There are lots of papers with projects to use ITMR (ion transport membrane reactors) for power plants, see review [5] but the use for vehicles exept ZEMPES is unknown. Such reactors are well in state of soon practical use due to achievements of Air Products and Chemicals and Norsk Hydro [6]. The recent available figures of measured oxygen flux[8] through membrane of 1.4 mm thickness, made of perovskite Ba Sr Co Fe O by T = 850 C are definitely about oxygen flux of 8 mL/cm2.min = 1.9g/sq.m.s

Most important work for our project has been done in ECN, Netherlands by Vente et al.[9] They discussed three different configuration of membranes in a reactor of a rather big size for practical applications. They admit the oxygen flux as 10 mL/cm2.min, which is near to measured data [8].In our calculations the modest figure of j= 1.9g/sq.m.s is used.
For the monolytic type of reactor assembled of tubes of outer diameter 200 mm with cannels of 1.5 mm and wall thickness 0.5 mm (Fig:6) they calculated the important parameter, the ratio of active surface to volume as 400 sq.m/cub.m. It is indicated by arrow in Fig.2.

For power 217 kW turbodiesel needs 1.102 mole/s of O2 or 35.26 g/s (table 2, point 29).. Assuming the surface/volume ratio as 400 sq.m/cub.m and j= 1.9g/sq.m.s we need surface of 35.264/1.9 = 18.56sq.m or the volume of active membranes as 0.0464 cub.m. By 0.2 m diameter the length of tubular reactor is 0.0464/0.0314 = 1.477m. It might be in two modules

of 0.75 m each. . By specific weight for heaviest ceramics (zirconia) of 6000 kg/cub.m and ceramic volume 0.64 of active volume (due to channels), its mass is 0.0464x0.64x6000 =178.17kg. Steel shell mass is:1.5x 3.14 x 0.2 x 0.002x8000 = 15.06kg.. The total mass of ITMR is 178.175+15.06=193.8 kg.
As the mass of prototyp diesel engine is 219 kg, the mass of ITMR is near. .. .

Here exists the principal problem of ZEMPES for vehicles – extra weight . There is three causes of additional weight : membrane reactor, high temperature heat exchanger H1 and liquid carbon dioxide onboard
The mass of prototype engine is 219 kg. Imagine the fuel mass as 51 kg, so total mass is 270kg ,by nominal power 52 kW, hence specific weight of prototype is 270/52 = 5.19 kg/kW.

The question is: zero emissions operation needs some additional equipment.Is it possible to increase power of turbodiesel to such extent as to conserve the specific weight ?
Next tables give the positive answer to this question due to increase the oxygen fraction in cylinder charge. If mass of produced and captured CO2 is three times of fuel mass, it means 153 kg , ITMR mass of193kg, and heat exchanger H1 of 50 kg (see later)the specific weight of turbodiesel is
(219 +153 +193.8 + 50)/217= 2.837kg/kW, which is about 2. times less than that of prototyp.

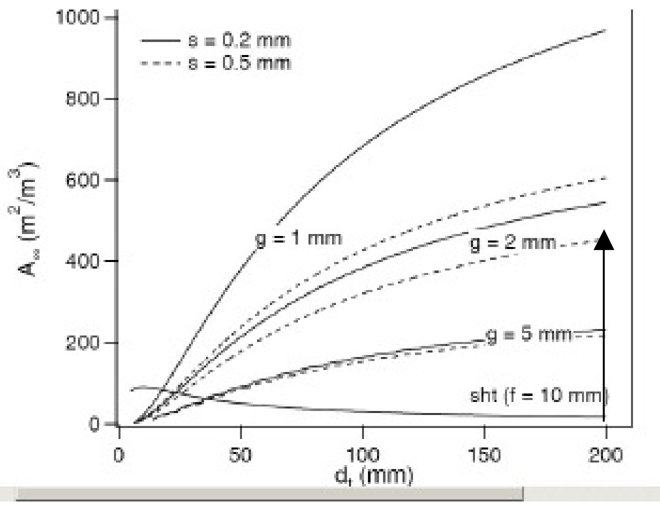


Fig.2. Geometrical properties of monolith ITM reactors of cylinder shape, calculated in [9] Arrow shows the design point, selected for turbodiesel. Selected parameters see also in Fig.5.

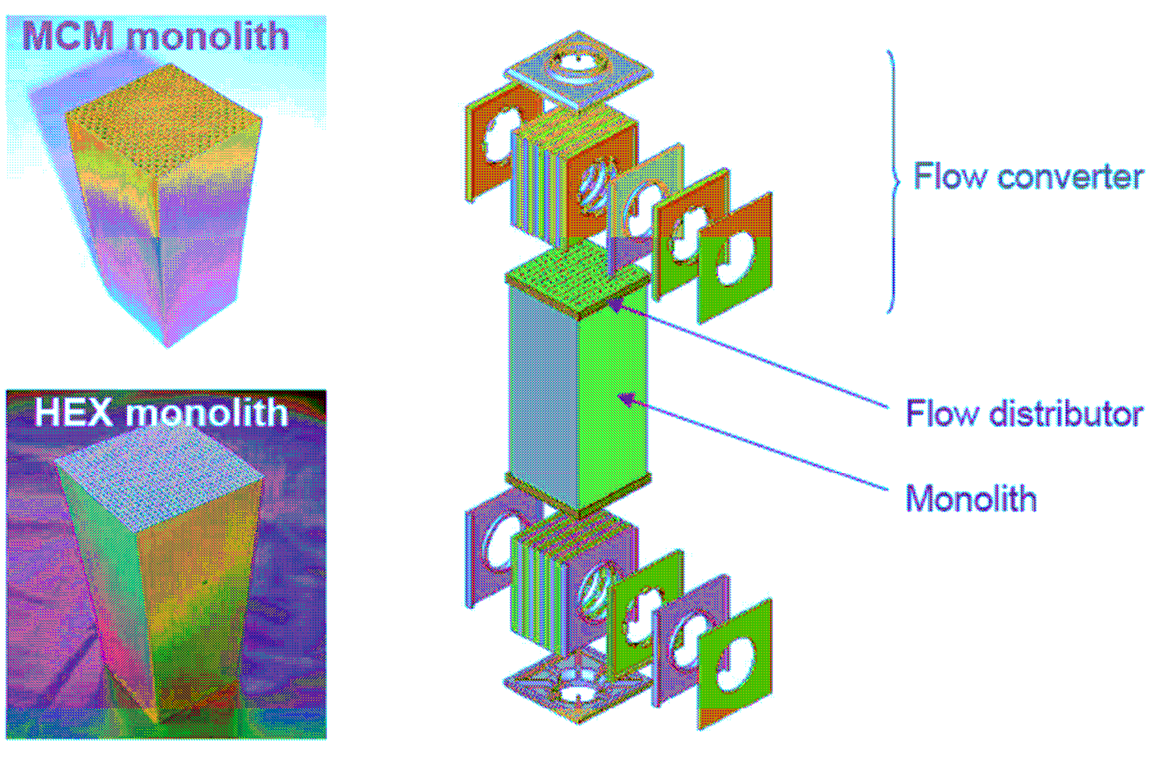


Fig.3.ITM reactor of monolith type, developed by Norsk Hydro. MCM = mixed conducting membrane, HEX = heat exchanger. A similar type is selected for turbodiesel, but for cylinder shape.

Numerical example

The well known diesel engine Ford-425 has been selected for calculations as a prototype. Manufacturers data are as follows: bore = 93.67 mm, stroke 90.54 mm, 4 cylinders, frequency 4000 r/min, volume 2.5 l, compression ratio 19.02, power 52 kW.
We have calculated the efficiencies: indicator 0.4779, mechanical 0.737, effective 0.3522.

Table 1 Calculated power and efficiency of turbodiesel

Oxygen fraction Q	0.209(air)	0.3	0.4	0.3	0.4
Excess coefficient α	1.7	1.4	1.4	2.0	2.0
Diesel fuel flow, g/s	3.473	5.6839	7.5785	3.9787	5.3049
Its thermal power,kW	147.41	241.26	321.67	168.88	225.17
Added fuel g/s	0	2.1795	2.9060	3.8142	5.0856
Added therm.pow.,kW	0	96.50	128.67	168.88	225.17
Total therm.power, kW	147.41	337.76	450.34	337.76	450.34
Diesel power, kW	52	66.68	90.65	45.14	64.5
Turbine power, kW	0	85.01	126.43	100.84	146.07
Total power, kW	**52**	**151.69**	**217.08**	**145.98**	**210.57**
Efficiency	**0.3522**	**0.4491**	**0.4820**	**0.4322**	**0.4676**

Here the first columne relates to prototype (diesel Ford 425) and other 4 columnes describe the turbodiesel. The table reveals the major role of turbine, due to 4 times power increase and significant efficiency gain with respect to the prototype:

.
Efficiency gain from 0.3522 up to 0.482 compensates the need to carry onboard rather heavy equipment.

In ZEMPES the use of membrane reactor gives an ability to govern the oxygen flowrate and quite independently change the both governing quantities: oxygen excess coefficient α (ratio of actual flowrate to the stoicheometric one) and oxygen fraction in mixture with CO_2 (different amount of O_2 in artificial air). In tables are used the fixed values only (1.4 or 2.0 and 0.3 or 0.4).
In Fig.5 is presented their interrelation, needed to maintain constant power or efficiency.

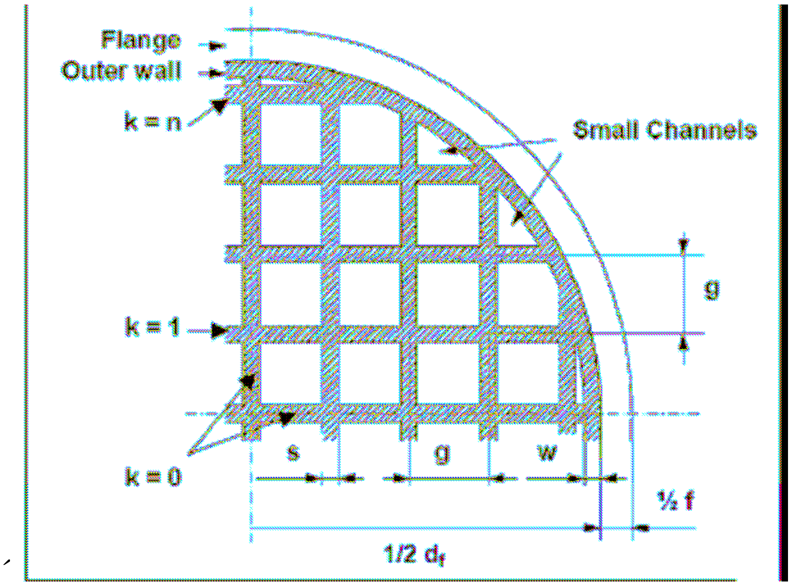


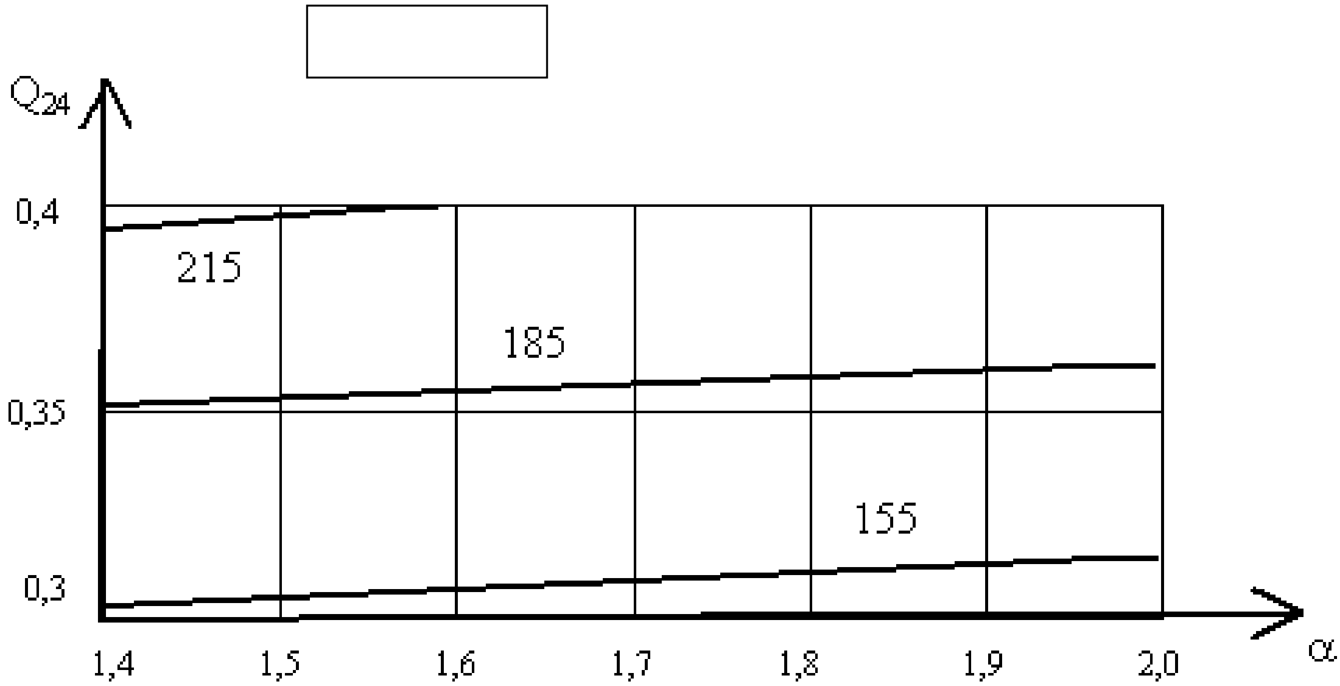
Fig.4 Cross section of one quarter of a multi-channel monolith ITM reactor selected for the turbodiesel: d_f= 200 mm, s= 0.5 mm, g=2 mm, f =4 mm. In Fig.2 for this case the surface/volume ratio is 400.

High temperature heat exchanger

Afterburner AK (see Fig.1) gives to the heat exchanger H1 very hot gas. Its energy is used to heat the compressed depleted air. In the Table 2 is seen the entrance temperature 2122 K (1849 C) which is too high to use here any heat exchanger of the best known steel. The only solution we see is the use well known material SiC, silicon carbide. It is quite stable even in oxidizing flow by such temperatures and is widely used for manufacturing by extrusion.
SiC is stable against thermal and mechanical shocks and does have high thermal conductivity. Good perspectives of ceramic heat exchangers for microturbines (just as in our case) forecasted C.McDonalds in a comprehensive review[11].

Our heat exchanger is similar to the ones of monolith type HEX, made by Norsk Hydro, see Fig.3. Because it is an important part of the turbodiesel the detailed data from a preliminary calculation to guess its mass and dimensions are given in the Table 3.

It was assumed an ideal thermal insulation without any loss of energy from H1. The radiation heat exchange has been neglected as well as conductive thermal resistance in SiC due to high thermal conductivity (490 W/m.K).



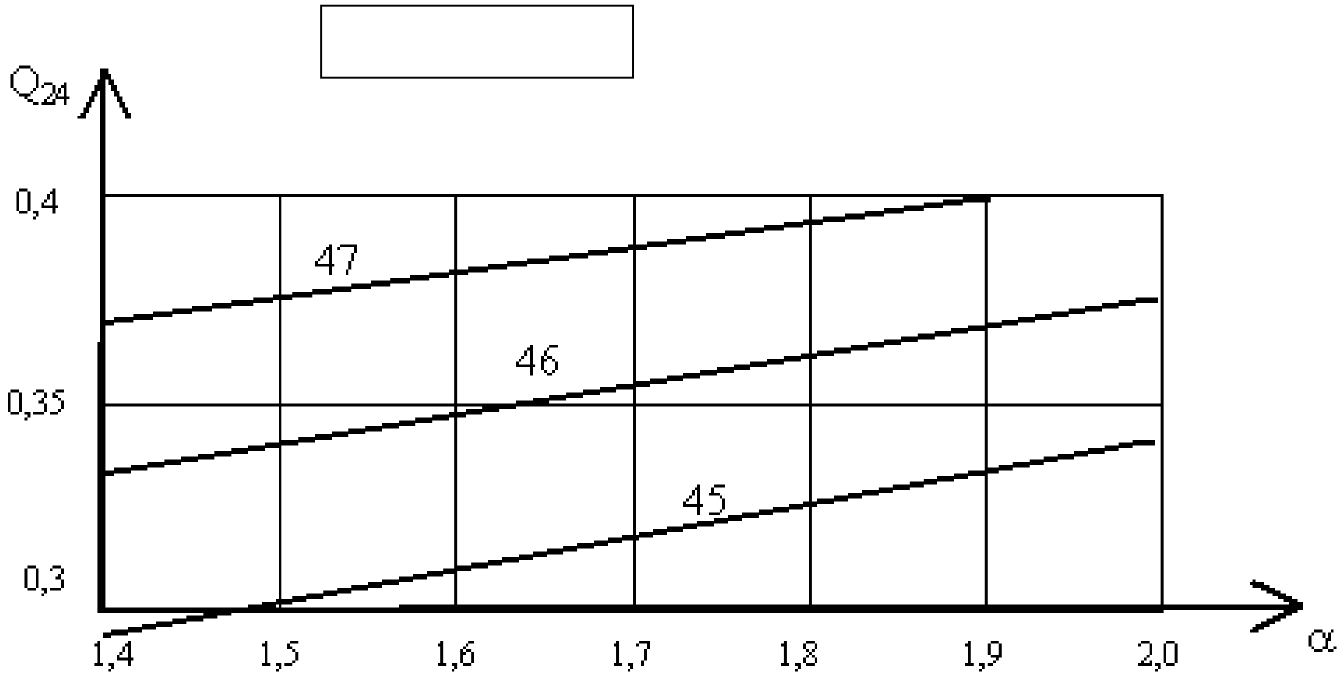


Fig.5 The link between oxygen fraction Q and excess coefficient α by constant power (above) and constant efficiency (below).

Table 2 Parameters in node points. T=temperature, K, M= mass flow, kmole/s. H= enthalpy flow, kJ/s

NN	P, MPa	Case 1			2			3			4		
		T, K	M,	H,	T	M	H	T	M	H	T	M	H
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0,101325	308	0,0027547	32,553	308	0,0027547	31,339	308	0,0027547	32,553	308	0,0027547	31,3385
2	0,101325	1249,4	0,0029412	165,02	1550,9	0,0030034	212,14	980,8	0,0028852	121,47	1205	0,0029288	151,51
3	0,101325	1780,3	0,0030229	260,91	2122,3	0,0031124	339,99	1939,2	0,0030283	289,27	2365	0,0031194	375,25
4	0,101325	1283	0,0030229	178,12	1283	0,0031124	181,25	1283	0,0030283	178,29	1283	0,0031194	181,44
5	0,101325	527	0,0030229	66,98	527	0,0031124	68,11	527	0,0030283	67,04	527	0,0031194	68,18
6	0,101325	308	0,00249	32,722	308	0,0024018	31,563	308	0,0024836	32,638	308	0,0023932	31,4505
7	0,101325	308	0,00192829	25,34	308	0,00165282	21,72	308	0,00192829	25,34	308	0,00165282	21,72
8	0,101325	308	0,000561736	7,382	308	0,000749	9,8426	308	0,0005553	7,2976	308	0,00074042	9,7301
9	0,101325	308	0,00053292	1,4059	308	0,00071056	1,8745	308	0,00054468	1,4369	308	0,00072624	1,91587
18	0,101325	288	0,013377	109,01	288	0,017718	144,39	288	0,0148408	120,94	288	0,0195415	159,25
19	0,607950	511,8	0,013377	197,1	511,8	0,017718	261,06	511,8	0,0148408	218,67	511,8	0,0195415	287,93
20	0,606450	1273	0,013377	519,06	1273	0,017718	687,5	1273	0,0148408	575,87	1273	0,0195415	758,28
21	0,606450	1273	0,0125504	486,99	1273	0,016616	644,75	1273	0,014014	543,8	1273	0,01844	715,51
22	0,604950	1468,5	0,0125504	569,79	1554,6	0,016616	803,49	1507,1	0,014014	654,78	1507,1	0,01844	909,32
23	0,101325	1017,4	0,0125504	381,96	1080,7	0,016616	539,71	1045,8	0,014014	439,32	1101,2	0,01844	611,2
24	0,101325	527,0	0,0125504	190,66	527	0,016616	252,42	527	0,014014	212,89	527	0,01844	280,13
27	0,101325	1273	0,00082641	32,067	1273	0,001102	42,761	1273	0,00082641	32,067	1273	0,001102	42,76
28	0,101325	527	0,00082641	12,554	527	0,001102	16,741	527	0,00082641	12,554	527	0,001102	16,741
29	0,101325	308	0,00082641	7,2136	308	0,001102	9,619	308	0,00082641	7,2136	308	0,001102	9,619

Table 3 Parameters of the heat exchanger H1

		Hot line (CO_2)	Cold line (air)
Mass flow mole/s	(g/s)	3.112 (130)	16.6 (481)
Temperature in ,	K	2122.3	1273
Temperature out,	K	1283	1554
Enthalpy in	kW	339.99	644.7
Enthalpy out	kW	181.25	803.49
Viscosity	Pa.s $.10^7$	655	674.4
Density	kg/cub.m	1.56	1.0
Therm.conductiv.	W/m.K	0.121	0.090
Velocity	m/s	10	25
Reinolds number	-	476	740
Nusselt number		1.8	2.0
Heat trans. Coef.	W/sq.m.K	109	128

The square channel of 2 mm side assumed in both lines. Overall heat transfer coefficient 58.8W/sq.m.K. Mean logarithmic temperature drop is 139 K. Mean specific heat current is 139x58.8=8173 W/sq.m. The heat transfer surface is 158.74/8.173=19.4 sq.m.

As a guaranty that such device might be manufactured of SiC by extrusion one may have a look at the Technology brief [10]. Cylinder device with passageway of 2 mm with the active surface 10.7 sq.m, diameter 142 mm and length 864 mm has the mass of about 25 kg .
For our example of turbodiesel is enough the two such cylinders, total mass 50 kg. It is not prohibiting even for a car

Conclusion

Calculations show the possible increase of power from 52 kW to 217 kW and efficiency from 35% up to 48% by conversion of a car diesel **to zero-emissions turbodiesel** with membrane oxygen reactor. The additional mass of membrane reactor is about of mass of prototype engine.Total mass of system in turbodiesel increased two times less than power. It justifies the further activity on turbodiesel project toward soonest demonstration.

THE EXISTING FLEET OF ELEVEN MLN DIESEL ENGINES IN USA MIGHT BE USED FOR CONVERSION IN THE ZERO EMISSION TURBODIESEL , SAVING MUCH INVESTMENT.

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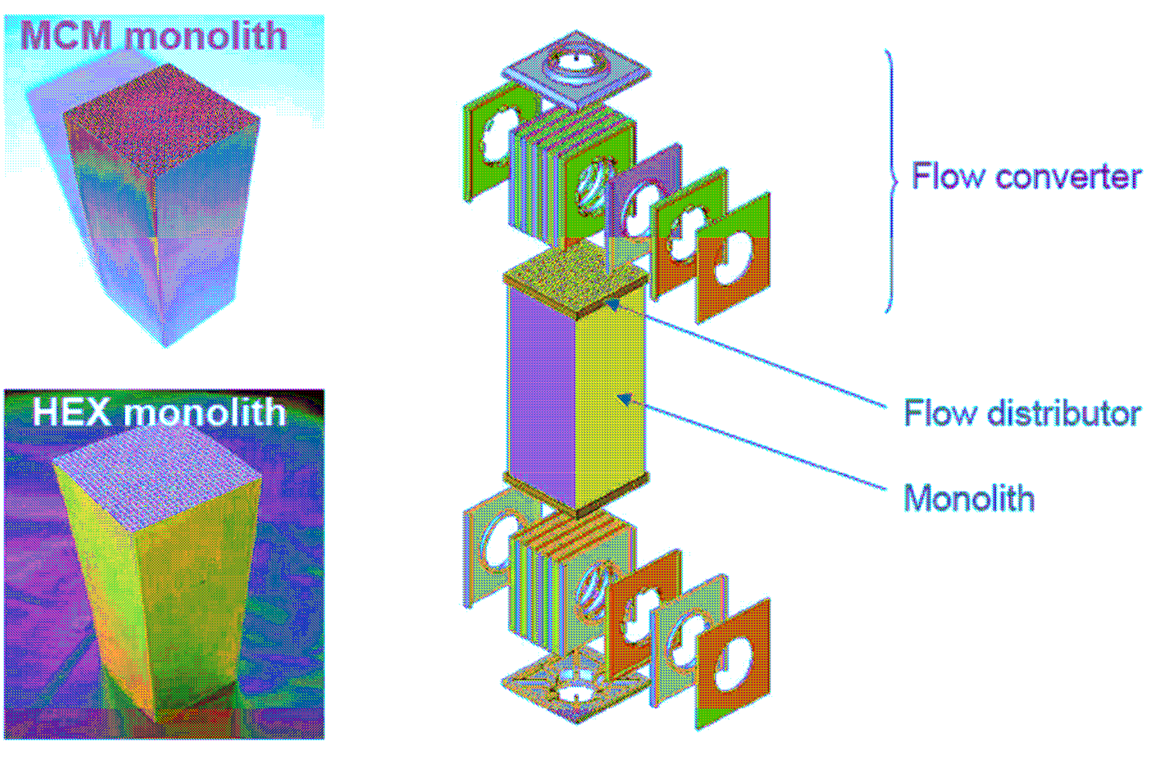
MCM monolith
HEX monolith
Flow converter
Flow distributor
Monolith

NN	P, MPa	Case 1			2			3			4		
		T, K	M,	H,	T	M	H	T	M	H	T	M	H
1	2	3	4	5	6	7	8	9	10	11	12	13	14
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22	0,604950	1468,5	0,0125504	569,79	1554,6	0,016616	803,49	1507,1	0,014014	654,78	1507,1	0,01844	909,32
23	0,101325	1017,4	0,0125504	381,96	1080,7	0,016616	539,71	1045,8	0,014014	439,32	1101,2	0,01844	611,2
24	0,101325	527,0	0,0125504	190,66	527	0,016616	252,42	527	0,014014	212,89	527	0,01844	280,13
27	0,101325	1273	0,00082641	32,067	1273	0,001102	42,761	1273	0,00082641	32,067	1273	0,001102	42,76
28	0,101325	527	0,00082641	12,554	527	0,001102	16,741	527	0,00082641	12,554	527	0,001102	16,741
29	0,101325	308	0,00082641	7,2136	308	0,001102	9,619	308	0,00082641	7,2136	308	0,001102	9,619