Exhaust gas toxicity problems in ship drives

Czesław Kolanek, Ph.D.
Zbigniew J. Sroka, Ph.D.
Wojciech W. Walkowiak, Ph.D.
Wroclaw University of Technology

ABSTRACT

The issues discussed in the article include exhaust gas emission, purity requirements and standards, methods of reducing the emission of harmful exhaust gas components, and alternative and future traction drive sources having the form of fuel cells. The discussion often refers to the situation of road transport, a subsystem which severely affects the environment and thus is obliged to intensify the search for solutions.

Keywords : inland navigation, diesel engine, fuel cell, emission, standards

INTRODUCTION

The transport system in each country is a basic component of the economic infrastructure. In many developed economic systems in the world the inland water transport is treated as an equivalent subsystem to other transportation forms [1]. Among other factors, its position results from the following qualities :

- ★ low power consumption
- ★ low noise emission
- ★ low environment pollution.

It is diesel engines that are used as driving units in inland navigation ships. Long-term and steady conditions of operation, along with technological achievements provide good opportunities for reducing the emission of toxic compounds in exhaust gases produced by a ship engine. But still these engines cannot be considered zero-emission devices.

EMISSION OF EXHAUST GASES

A fuel which is commonly used for feeding ship drive diesel engines is hydrocarbon fuel produced in the process of crude oil processing. The chemical energy of the fuel is converted into thermal energy in the combustion (oxidation) process executed in the engine cylinder. Then the thermal energy is converter into mechanical energy having the form of a torque transmitted to the flywheel.

The process of oxidation of carbon and hydrogen, which are fuel components, makes use of the oxygen taken from the atmospheric air, another component of which, with 79% share, is nitrogen, which also takes part in the combustion process.

Crude oil is accompanied by sulphur. Its concentration in the fuel produced from the crude oil is controlled, but the cost of processes aimed at sulphur removal is directly proportional to the removed volume.

The execution of the combustion process in the diesel engine requires excessive air volumes, defined by the air excess coefficient λ.

Products generated in the combustion process include toxic compounds, such as C_uH_v , CO, C, SO_z , NO_x . Amorphous carbon C is not toxic, but due to its ability to absorb liquid and gas components of the exhaust gas on its surface it is defined as a controlled and limited component, bearing the name of solid particles (PM or PT).

The emission of exhaust gases is directly proportional to the engine piston displacement volume (V_{ss}) and engine crankshaft rotational speed (n). Percentage composition of the exhaust gas mainly depends on the combustion system and the engine load represented by its torque (M_o).

EXHAUST GAS PURITY REQUIREMENTS AND STANDARDS

It is diesel engines which are most frequently used as inland ship drives. During the first stage of legislation activities oriented on standardising the emission of toxic compounds in exhaust gases, diesel engines composed a preferred group, with ten times as small concentration of carbon monoxide as that characteristic for spark-ignited engines. This situation changed when engine smoking, with the only reference to diesel engines, was to be reduced.

Design properties and operating characteristics were the factors deciding in favour of the domination of those engines used as high-power drives, while the development of research techniques allowed standardising so-called unit emissions, expressed in g/kWh, of four main exhaust gas components, which were CO, HC, NO_x and PM.

Table 1 collects EU Standards concerning emission limits for so-called off-road engines (closest to inland ship drives), taken from the instructions [2].

***Table 1**. Emission limits for off-road engines [2].*

PN	In force since	CO	HC	NO_x	PM
KW	-	[g/kWh]			
Stage I					
130 – 560	1999.01	5.0	1.3	9.2	0.54
75 – 130	1999.01	5.0	1.3	9.2	0.70
37 – 75	1999.04	6.5	1.3	9.2	0.85
Stage II					
130 – 560	2002.01	3.5	1.0	6.0	0.2
75 – 130	2003.01	5.0	1.0	6.0	0.3
37 – 75	2004.01	5.0	1.3	7.0	0.4
18 – 37	2001.01	5.5	1.5	8.0	0.8

Table 2 collects EU Standards concerning emission limits for inland transport engines, taken from the instructions [3].

***Table 2**. Emission limits for inland transport engines – Stage III [3].*

Category	Piston displacement volume (D) Engine power (P)	CO	NO_x + HC	PM	In force since
-	[D, cm^3] [P, kW]	[g/kWh]			[-]
V1:1	D ≤ 0.9 and P > 37	5.0	7.5	0.40	31.12.2006
V1:2	0.9 < D ≤ 1.2	5.0	7.2	0.30	
V1:3	1.2 < D ≤ 2.5	5.0	7.2	0.20	
V1:4	2.5 < D ≤ 5.0	5.0	7.2	0.20	31.12.2008
V2:1	5.0 < D ≤ 15	5.0	7.8	0.27	
V2:2	15<D≤20 and P≤3300	5.0	8.7	0.50	
V2:3	15<D≤20 and P>3300	5.0	9.8	0.50	
V2:4	20 < D ≤ 25	5.0	9.8	0.50	
V2:5	25 < D ≤ 30	5.0	11.0	0.50	

The situation in Poland is regulated by the act [4], which only standardises exhaust gas smokiness (using the light absorption method) in diesel engines at the level equal to :

- 2.5 m^{-1} for engines without superchargers
- 3.0 m^{-1} for supercharged engines.

The International Maritime Organisation (IMO) determines, in turn, only NO_x emission. Sample emission limits for engines of more than 130 kW output are given in Table 3 [5].

***Table 3.** NO_x emission limits according to IMO regulations [5].*

Engine rotational speed n [rev/min]	NO_x [g/kWh]
n < 130	17.0
130 ≤ n < 2000	$45n^{(-0.2)}$
n ≥ 2000	9.8

As a comparison, Table 4 collects emission limits defined by the Environment Protection Agency (EPA) for engines of more than 37 kW output [6] :

***Table 4.** Emission limits according to EPA regulations for engines of more than 37kW output [6].*

Category	Piston displacement volume D	CO	NO_x + THC*	PM	In force since
-	[dm^3]	[g/kWh]			[-]
Base form – off-road engine	D<0.9	5.0	7.5	0.40	2005
	D<1.2	5.0	7.2	0.30	2004
	D<2.5	5.0	7.2	0.20	2004
	D<5.0	5.0	7.2	0.20	2007**
*) THC (Total Hydro Carbons) **) Stage I (Tier 1) in force since 2004					

The experience in organization and management of water transport on the Rhine River is used for legislative activities in other areas. For better orientation in regulation tendencies, the regulation rules of the tests to be performed on Rhine ships (RheinSchUO) are quoted. These regulations introduce since 1 July, 2007, the second level of emission limits for engines used in Rhine navigation [7]. These limits have been collected in Table 5.

Since the „old" fleet is still in use, the transitory regulations were issued as well.

***Table 5.** Emission limits in Rhine navigation, in force since 1st July 2007. [7].*

P_N [kW]	CO [g/kWh]	HC [g/kWh]	NO_x [g/kWh]	PT [g/kWh]
$19 \le P_N < 37$	5.0	1.5	8.0	0.8
$37 \le P_N < 75$	5.0	1.3	7.0	0.4
$75 \le P_N < 130$	5.0	1.0	6.0	0.3
$130 \le P_N < 560$	3.5	1.0	6.0	0.2
$P_N \ge 560$	3.5	1.0	n ≥3150 min^{-1} =6.0 343≤n<3150 min^{-1} =$45n^{(0.2)}$-3 n<343 min^{-1} =11.0	0.2

The limits given in Table 5 do not apply to :

a) engines installed on ships before 1st January 2003
b) replacement engines (used engines, after overhaul, which are similar to those replaced with respect to parameters and installation conditions), to be installed before 31th December 2011, on ships, which were in operation on 1st January 2002. For engines which were installed on ships before 1st July 2007, emission limits given in Table 6 are in force.

***Table 6.** Transitory emission limits in Rhine navigation [8].*

P_N [kW]	CO [g/kWh]	HC [g/kWh]	NO_x [g/kWh]	PT [g/kWh]
$37 \le P_N < 75$	6.5	1.3	9.2	0.85
$75 \le P_N < 130$	5.0	1.3	9.2	0.70
$P_N \ge 130$	5.0	1.3	n ≥2800 min^{-1} =9.2 500≤n<2800 min^{-1} =$45n^{(0.2)}$	0.54

Along with RheinSchUO regulations, the European Union defines limits for inland ship engines. Since 2007, engines newly installed on ships sailing outside the Rhine River have to obey the regulations, whose limits are identical to those in force on the Rhine River.

METHODS REDUCING THE EMISSION OF HARMFUL EXHAUST GAS COMPONENTS

Methods used for reducing the emission of toxic components to the atmosphere can be divided into active (which interfere in engine settings and the combustion process) and passive (purification of exhaust gases emitted by the engine). It should be mentioned here that these methods mainly refer to diesel engines.

Active methods :

- optimising the fuel injection starting angle
- modifying the fuel ignition process
- changing the combustion system
- supercharging
- reducing the compression ratio
- exhaust gas recirculation
- introducing water to the combustion process
- using alternative fuels.

Passive methods :

- catalytic methods of CO and HC oxidation
- non-catalytic and catalytic methods of NO_x reduction
- reducing the emission of solid particles, PT, with the aid of filters.

The analysis of active methods allows a conclusion to be formulated that further interference in engine construction, combustion process, and-or settings will not return expected effects, as it is not possible to minimise at the same time the emission of all harmful substances. Always a conflict will be observed when taking actions to reduce the contents of NO_x and HC, and solid particles [9 – 18].

Solutions which could positively affect the emission of all harmful components of the exhaust gas are already known and used (exhaust gas recirculation, supercharging, catalytic techniques). To meet exhaust gas purity standards, which are becoming more and more severe, passive methods of reduction are to be developed and-or other technical solutions are to be looked for.

The effects of the used and prognosed solutions, taking into account a so-called conflict between NO_x and PM emission reduction goals, are shown in Fig.1 [19].

The emission of harmful exhaust gas components was effectively reduced by developing high-pressure fuel injection systems and introducing the below presented systems of exhaust gas “processing”.

The exhaust gas outlet system equipped with an oxidising catalyst and solid particle filter, and making use of fuel additives to facilitate the regeneration, is schematically shown in Fig.2.

The engine outlet system with a NO_x accumulating catalyst (so-called denox catalyst) is given in Fig.3.

The outlet arrangement with a system of selective catalytic reduction (SCR) is shown schematically in Fig.4.

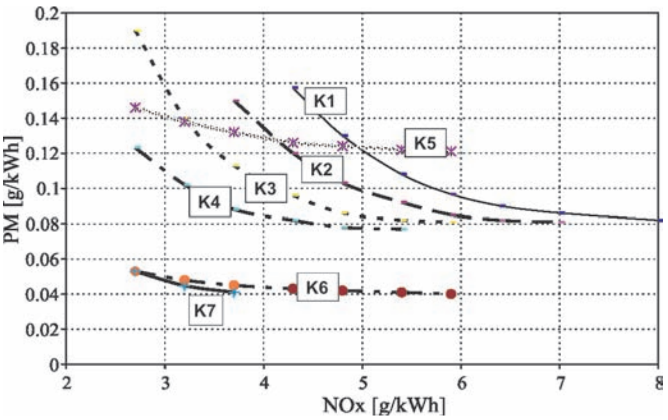

*Fig. 1. Measured and expected volumes of NO_x and PM emission for high-load diesel engine : **K1** - reference engine, **K2**, K3, K4 - engine with denox catalyst revealing efficiency equal to 15%, 30%, 45%, respectively, **K5** - EGR (exhaust gas recirculation), **K6** - EGR + exhaust gas cooling + PM filter, **K7** - denox catalyst + PM filter [19].*

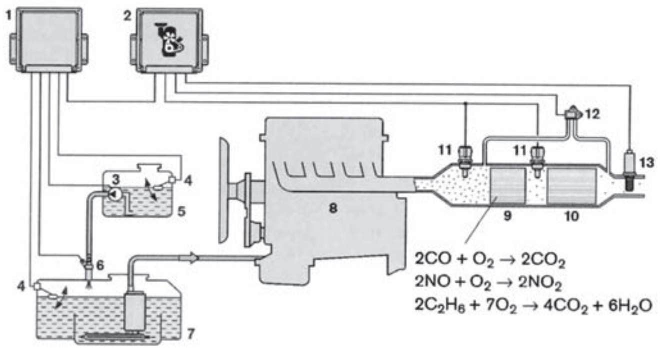

*Fig. 2. Schematic of exhaust gas outlet system equipped with oxidising catalyst and solid particle filter, and making use of fuel additives : **1.** fuel additive controller, **2.** engine controller, **3.** fuel additive pump, **4.** fuel additive level sensor, **5.** fuel additive tank, **6.** additive proportioning apparatus, **7.** fuel tank, **8.** diesel engine, **9.** oxidising catalyst DOC, **10.** solid particle filter, **11.** temperature sensor, **12.** pressure difference sensor, **13.** soot sensor [20].*

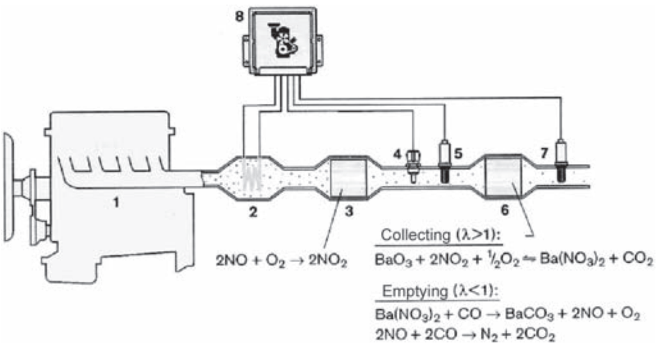

*Fig. 3. Schematic of engine outlet system with NO_x accumulating catalyst : **1.** engine, **2.** exhaust gas heating (optional), **3.** oxidising catalyst (optional), **4.** temperature sensor, **5.** wide-band lambda probe, **6.** NO_x accumulating catalyst, **7.** NO_x sensor or lambda probe, **8.** engine controller [20].*

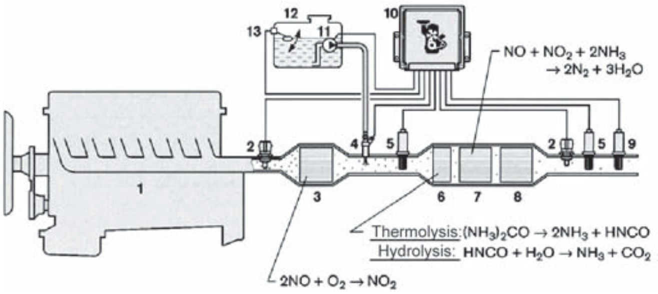

*Fig. 4. Schematic of SCR system : **1.** engine, **2.** temperature sensor, **3.** oxidising catalyst, **4.** reducer injection nozzle, **5.** NO_x sensor, **6.** hydrolytic catalyst, **7.** SCR catalyst, **8.** NH_3 blockage catalyst, **9.** NH_3 sensor, **10.** engine controller, **11.** reducer pump, **12.** reducer tank, **13.** reducer level sensor [20].*

THREATS AND PERSPECTIVES

The above presented solutions base on the principle of permanent development of methods reducing the emission of toxic compounds, with the simultaneous reduction of costs of their application, assuming that the objects of interest are classical engines in operation, fuelled by classical oil product or alternative fuel.

A multi-aspect analysis performed by the Natural Resources Defense Council (USA) on the resources of primary energy sources, effects of operation of diesel engines, and technical abilities of the epoch, provides opportunities for expecting that the situation will develop in the following directions [21] :

- decreasing number and mileage share of new vehicles driven by conventional combustion engines (Fig. 5 and 6)
- temporal increase in the number and mileage share of new hybrid combustion-electric engine driven vehicles (Fig. 7 and 8)
- increase in share of new vehicles driven by so-called fuel cells (Fig. 9), a drive making use of alternative fuel in the form of hydrogen or its products.

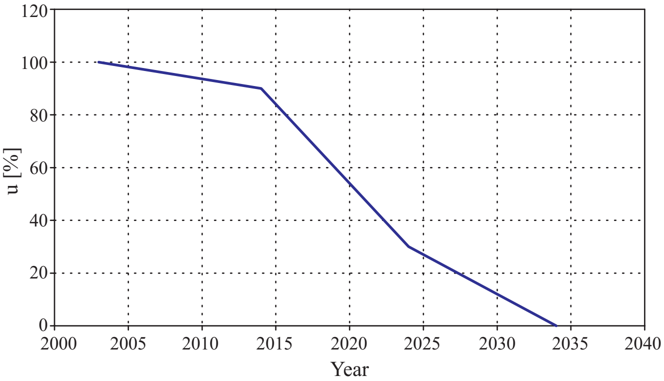

Fig. 5. Expected share of new vehicles driven by combustion engines [21].

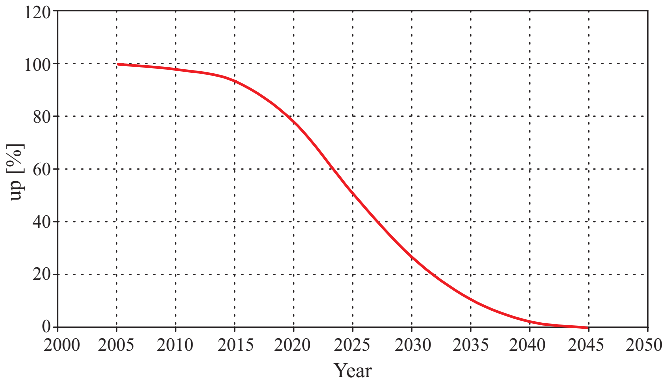

Fig. 6. *Expected mileage share of vehicles driven by conventional engines [21] .*

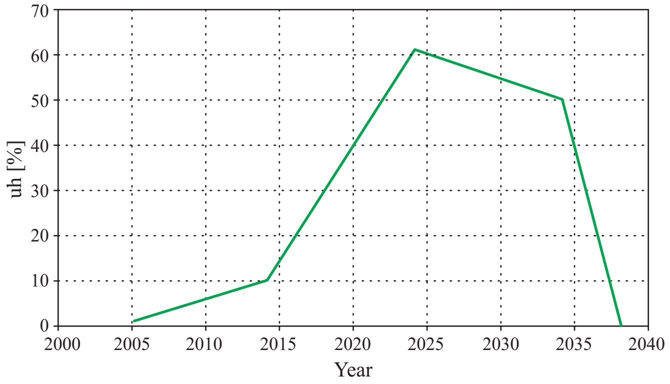

Fig. 7. *Expected share of new hybrid vehicles [21] .*

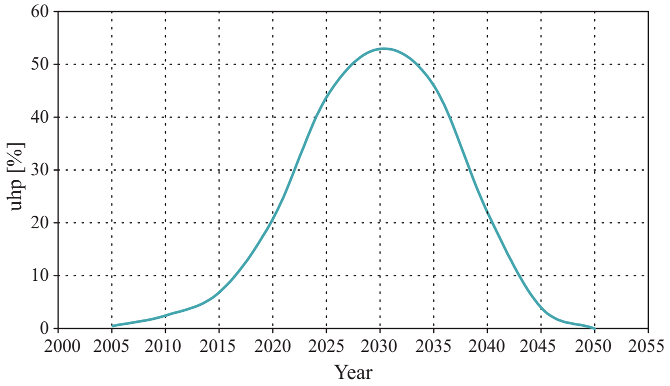

Fig. 8. *Expected share of hybrid vehicles in total mileage [21] .*

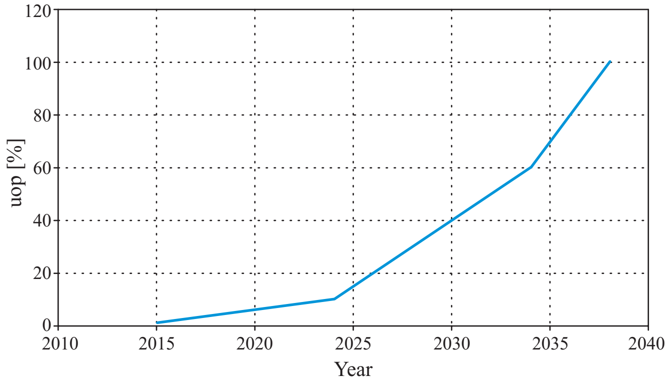

Fig. 9. *Expected share of new vehicles driven by fuel cells [21] .*

ALTERNATIVE PRIME MOVERS

Renewable energy sources include solar energy and light, water energy, biomass and wind energy. Renewable raw materials are plants which can be used for producing, in practice, all products which are now produced by the chemical industry from fossil materials [22].

A common and direct source of all renewable resources is the Sun. The potential of the solar energy and that of renewable raw materials is many times as big as the potential represented by fossil fuels.

The Sun delivers to the Earth fifteen times as much energy per year as that representing the annual consumption of nuclear energy and the energy produced from fossil fuels. Italy alone receives six times as much solar energy as the annual world energy consumption. The annual photosynthetic capacity of the flora exceeds the annual production of chemical industry by ten thousand times.

And that is why replacing the potential of fossil resources by the solar energy is quite possible.

The potential of the solar energy is characterised by three common properties which are in opposition to those specific of fossil resources.

Firstly, its capacity cannot be exhausted as long as the solar system exists, which means an approximate time period of five milliard years of Earth's future. This fact alone can prevent a world ecological crisis.

Secondly, processing these resources into the energy and secondary materials (heat, fuel, electricity) is not accompanied by the emission of impurities, or – like in case in biomass – the emission is so small that does not present a threat to our global environment.

Thirdly, the solar energy is fully or partially available everywhere, and its collection has to take a decentralised and regional course.

Making use of solar energy does not require global delivery chains. What it needs is good energy conversion technique, which can be applied locally. Since the resources of solar energy are not in a concentrated form, their use requires manufacturing large numbers of small devices, resigning from small numbers of big investment projects in favour of many much smaller projects, and resigning from buying foreign energy in favour of regional and individual self-supply.

All this means breaking residential limitations introduced in the past by the fossil resource management. At the same time, it allows us to link the areas on which this energy is collected with those on which it is consumed.

Making use of solar energy based resources means, as a further consequence, creation of regional markets and their co-existence with global technology markets – but oriented on dispersedly used energy conversion techniques.

Such a situation leads to balancing chances of all national economies, both with respect to regional collection of energy resources, and permanent regionalisation of economic circulation.

Moreover, being a source of raw materials for industrial production agriculture and forestry, which are the primary forms of economy, will take greater weight.

In the history of human civilisation, the epoch of solar energy is a sign of an expected switch from agglomeration to deglomeration. Since the economic activity must follow the location of energy sources, decentralisation of the energy sources will lead to its territorial dispersion. Due to technical reasons, the world solar economy will make concentration of resources and capital impossible.

Since the solar energy is inexhaustible, it will provide a basis for a long-lasting model of human civilisation. And since the Sun cannot be privatised, no one can threat basic rules of this civilisation.

It is therefore possible and advisable to substitute fossil fuels for solar energy.

Solar energy

Due to its changing availability, which depends on the season, part of a day, and weather conditions, the solar energy is to be converted and stored [23].

Energy conversion can be executed in :

- **field solar power plants** – in which the solar radiation is directly converted into electric energy in photo-voltaic cells
- **solar thermal power stations** – in which the solar radiation is focused, using cylindrical mirrors, on a system of pipes with water circulating inside. The generated steam drives turbines of the turbosets
- **tower-type solar power plants** – in which mirrors focus solar radiation on a power tower, thus providing opportunities for the creation of extremely high temperatures inside. These temperatures are then used for generation of heat and electric current
- **funnel-type solar power plants** – in which the air heated in a large-dimension greenhouse is then transported outside through a high funnel (of a kilometre in length). The resultant pressure difference forces the air to move and drive air turbines connected with the current generator
- **dish-type solar power plants** – in which dish-shaped mirrors are used for local production of thermal energy.

The generated electric current and heat can be used for current purposes in industrial activity and for living needs. Surplus volumes can be stored or exported using intercontinental transport grids.

The stored electric current can be used as an independent source of energy for driving vehicles. Electric current accumulators, available now on the market, are not very attractive, however, despite high efficiency revealed by the electric drive system.

An alternative solution can be the use of electric energy for the production of hydrogen, which then can be used as energy carrier. The hydrogen obtained in this way will be delivered using pipelines and tankers to industrial centres, where it can be used for producing thermal energy, for supplying classical gasoline engines of both stationary and traction types, and-or for producing electric energy in fuel cells, which offer the highest efficiency of conversion of the chemical energy collected in the fuel into the mechanical energy driving the vehicle (Fig.10).

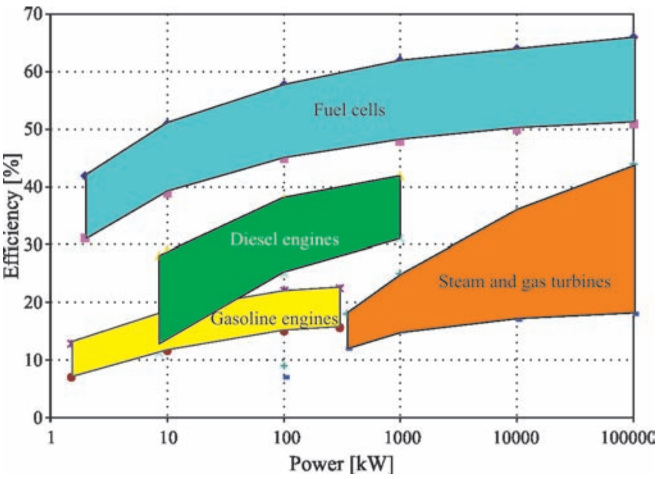

Fig. 10. Efficiency of different energy converters [24].

Use of hydrogen

Known since 1838, the controlled reaction between the hydrogen and oxygen in a fuel cell is considered a key technology of ecological energy production.

Electrochemical reactions taking place in different types of fuel cells are collected in Fig.11.

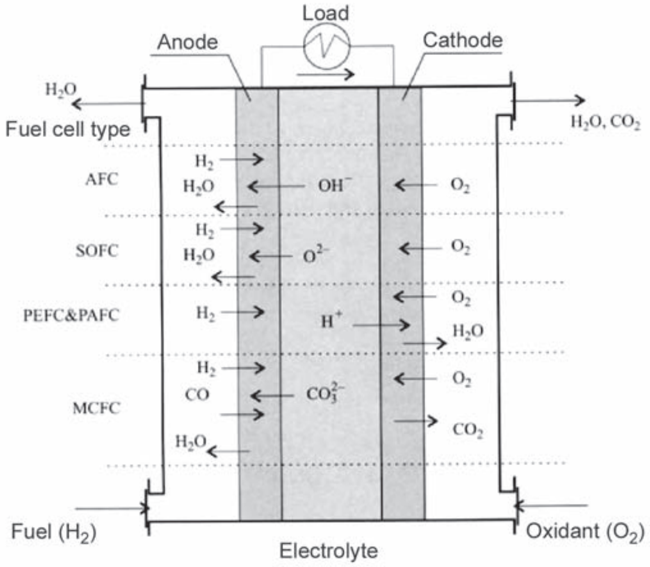

*Fig. 11. Electrochemical reactions taking place in different types of fuel cells : **AFC** (Alkaline Fuel Cell) – alkaline reactions; **SOFC** (Solid Oxide Fuel Cell) – oxide reactions, **PEFC** (Polymer Electrolyte Fuel Cell) – – polymer reactions, also labelled as **PEM** (Proton Exchange Membrane); **PAFC** (Phosphoric Acid Fuel Cell) – acid reactions; **MCFC** (Molten Carbonate Fuel Cell) – carbonate reactions [25].*

It is a hydrogen fuel cell, making use of proton membrane and bearing the name of PEMFC (Proton Exchange Membrane Fuel Cell), see Fig.12, which is considered the most promising, especially in traction applications.

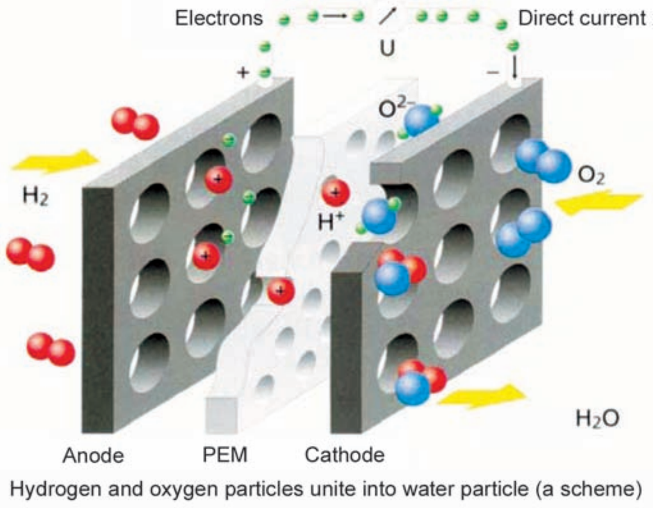

Fig. 12. Scheme of PEM fuel cell [27].

A foil covered with a layer of a catalyst, mainly platinum, is placed between electrodes in the cell. The catalyst accelerates ionisation of the hydrogen, while the membrane allows positively charged ions to pass to the side washed by the oxygen where they unite into water particles.

The reactions taking place on cell electrodes can be written in the following way :

$$\text{anode} : 2H_2 = 4H^+ + 4e^-$$
$$\text{cathode} : O_2 + 4H^+ = 2H_2O$$

The electrons which stay on the "hydrogen" side produce negative charge, while on the "oxygen" side a positive charge is produced, all this leading to the creation of the potential difference of 0.6-0.9V in each cell, with the current density up to 250 mA/cm^2, which corresponds to power ranges between 0.15-0.45 W/cm^2. The temperature of operation of such a cell is equal to 80 Celsius degrees.

The power which can be obtained after combining those cells into a package is equal to 30-50 kW, at the device dimensions allowing it to be placed inside a car.

Using fuel cells in cars is connected with certain constructional limitations and problems. Prototypes which are in operation now require about 3 minutes for start, which suggests installing an additional source of energy to be used during this time. Fuel cells need hydrogen, which has to be stored as liquefied gas, (temperature -253ºC) or bounded in hydrides of metals in volumes securing reliable mileage reach. Moreover, the distribution network for this type of gas can hardly be considered satisfying. Therefore it is necessary to find an effective method of on-line hydrogen production in a car, for instance from methanol.

Applying the methanol would provide opportunities for using fuel in the liquefied form, convenient and safe in distribution. This fuel would be decomposed in a deck reactor (reformer) into hydrogen, used then as a fuel in the PEM cell, and waste CO_2 , which slightly spoils the image of a zero-emission vehicle.

Due to the highest output, it is a method decomposing the mixture of water and methanol vapours in the presence of a catalyst which seems to be the most promising for supplying traction fuel cells This method requires an additional burner for heating and evaporating the mixture, and supersaturating the vapour. The produced vapour is directed onto the Cu/ZnO catalyst and converted into a hydrogen-rich gas, which also contains undesirable CO, CO_2 , as well as small volumes of methanol and formaldehydes. Such a mixture cannot be directly passed onto the platinum catalyst in the fuel cell, which forces the use of additional installation for gas processing, including after-burning of the carbon monoxide, its absorption or filtering the products of the reforming by another membrane, of palladium-silver type for instance, which passes only hydrogen.

What makes the situation even more complicated, the reformer is to be heated to the temperature of 200 ÷ 300°C during its operation. The source of heat is a catalytic burner to burn gases which have been filtered from the hydrogen. The burner emits small volumes of CO_2 and negligibly small volumes of CO.

The above description reveals complexity of the fuel installation making use of hydrogen-oxygen cells, especially when the hydrogen is stored in the form of methanol.

The installation must include :

- ☆ methanol tank
- ☆ reformer with evaporator, burner, etc.
- ☆ installation for purification of the products of reforming
- ☆ hydrogen tank for starting the cell and supplying it in transient states
- ☆ fuel cell with own heat exchanger, tank for water generated by the cell and used for reforming
- ☆ additional batteries which drive the vehicle before the fuel cell is started and collect braking power
- ☆ control system.

The use of such numerous devices increases the cost of the entire installation, and requires proper space for it in the vehicle.

Applications of fuel cells

Advantages of fuel cells include clean and quiet operation, possible use of various types of fuel and high resistance to unfavourable atmospheric phenomena.

Fuel cells deliver energy in the form of direct current, while the in-home and industrial receivers are adapted to alternating current. As a result, the current produced in the cells is to be converted, which requires relevant converters.

In the developed countries much attention is paid to the use of fuel cells for producing heat and electric power. For some years fuel cells with power output up to 200 kW have supplied industrial installations, and have also been used as emergency generators. Fuel cells are being more and more frequently used in sewage treatment plants, composting plants, food processing plants, electric devices that do not tolerate supply breaks, and ecologically clean devices.

In the first three applications on the above list fuel cells are fed with methane, which otherwise would be undesired waste product.

At present, the cost of electric energy production from fuel cells is equal to $3000-4000 per kilowatt (data from 2002). And the price of a 200-kW device (based on SOFC technology) is equal to about $1.000.000. The producer makes this price depend on the goal of the planned application. The time of delivery is approximately equal to 2-3 months from the date of contract signature.

Large stationary fuel cells which were used in electric power plants in recent few years did not stand the test. For instance, 2 MW devices tested in Santa Clara, California, in 1995 rarely produced power exceeding 1 MW, which is only half of their design power [28].

Due to various problems, designers and producers of fuel cells focused their attention on devices with power output not exceeding 50 kW, intended for supplying one-family houses, residential buildings and small businesses, as well as to be used as traction power units [29].

Within the framework of the EU project, since 2002 city buses driven by fuel cells have been used in three European cities: Berlin, Copenhagen and Lisbon.

The MAN bus, weighting 18 Mg and 12 m long, is equipped with three sets of fuel cells produced by Nuvera, Italy. These fuel cells, the total power output of which is equal to 120 kW, drive two engines, produced by Siemens, with total power of 2 x 75 kW. The fuel in the form of liquid hydrogen is collected in tanks of total volume equal to 600-dm^{3,} located on the roof of the bus. This installation allows the bus to cover the mileage ranging up to 400 km [30].

Activities performed in the USA are oriented on prototype fuel cells revealing power output of 625 kW and 500 kW, making use of diesel oil as the fuel, and intended for driving submarines [31].

Three submarines of 212 and 214 class (out of a series of four) with the fuel cell based driving system were built in the shipyard Howaldtswerke-Deutsche Werft GmbH (Germany) [32].

The presented overview of applications of fuel cells confirms vast interest in this type of a source of drive. A wide spectrum of present applications allows us to expect extensive information to appear on its applicability as driving systems in navigation.

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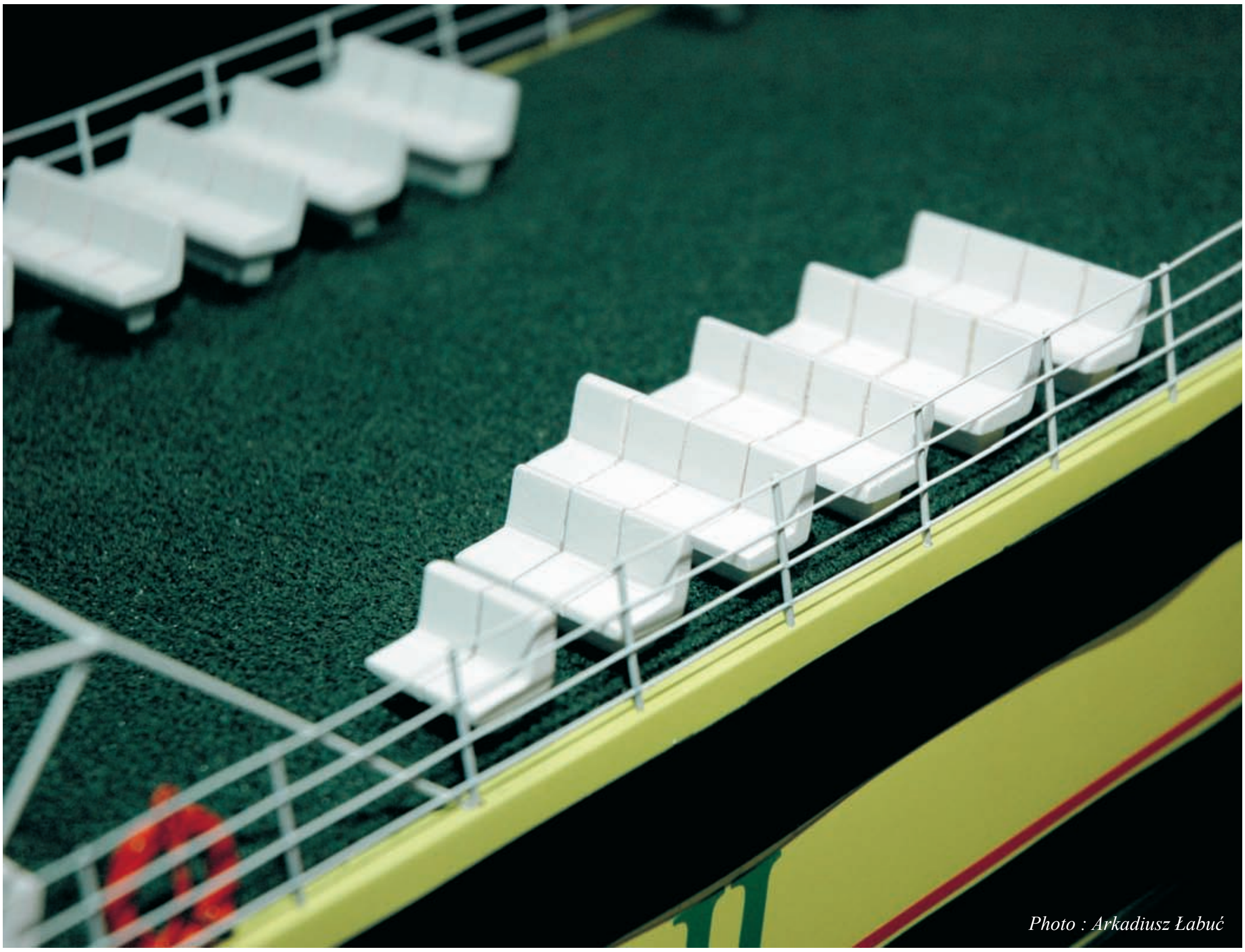

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