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High-temperature catalysis driven by the direct action of concentrated light or a high-density electron beam

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Abstract

Steam reforming of methane has been studied under direct illumination of a catalyst by concentrated light in an energy receiver/catalytic reactor unit with a light transparent wall. In such a reactor, the energetic efficiency η of the light-to-chemical energy conversion is about 50–75%, both the specific rate r of hydrogen production and the specific power loading w are extremely high, reaching 40 N cm^3/s per 1 cm^3 of the catalyst and 90–100 W/cm^3, respectively. Dependencies of r and w upon the incident power density and the methane conversion have been investigated. The data obtained are compared with those for nontransparent (steel) reactors as well as for reactors irradiated by high-power electron beam. Mechanism of the reaction rate enhancement as well as the influence of the reaction, catalyst and radiation nature on peculiarities of radiation-to-chemical energy conversion are discussed. © 1997 Elsevier Science B.V.

Keywords: Light-driven catalysis; Radiation energy conversion; Steam reforming of methane; Solar energy

1. Introduction

Solar energy is recognized as a promising source of energy even for the near future because of its enormous overall flux reaching the earth's surface, and its ecological friendliness. However, there are three main obstacles that prevent now a wide practical use of solar radiation: first, a low-density of the energy flux (less than 1 kW/m^2), second, unsteady behavior of this flux during a day or a season, and third, a necessity for the solar energy to be converted into a form which is suitable for its storage and further utilization, for instance, into chemical energy or electricity.

Photochemical or photocatalytic conversion of solar energy allows utilization of photons at low temperature directly to chemical fuels (H_2, CH_4, CH_3OH, etc.) without preliminary concentration of solar light. This approach to the solar energy utilization is under extensive development [1]. However, both the experimental experience in this field as well as some theoretical considerations are showing two main disadvantages of the quantum methods of the light-to-chemical energy conversion. These are: (a) a low efficiency η of energy conversion (for the single level molecular converting systems a thermodynamic limit for η is about 30% [1]); and (b) low specific power loading of the energy transformation, respectively.

An alternative approach to conversion of solar energy which is free of these shortcomings appears to be a high-temperature thermochemistry driven by concentrated solar light. A great long-term importance of this approach has been declared at the last Symposia

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on Solar High-Temperature Technologies [2–4]. Thermochemical conversion and storage of solar energy is based on accomplishing an endothermic chemical reaction at high temperature $T > T^*$, where T^* is a "shift" temperature at which the change of the Gibbs potential during the reaction is equal to zero ($\Delta G(T^*) = 0$). At the first stage of energy conversion, the concentrated solar energy is used for heating the reagents to the temperature $T > T^*$ and transforming to chemical energy of the reaction products, thus being accumulated. To release the stored energy, a reverse exothermic reaction should be performed at the proper conditions. The thermocatalytic approach to the conversion of radiation energy is characterized by rather high efficiency η, its thermodynamic limit for the enthalpy storing is close to 100% [5,6]. Solar catalytic reactors based on methane reforming with steam or carbon dioxide have been constructed and tested [7]. They are characterized by the efficiency of about 50% and the useful output power of about 2 kW.

Additionally, a theoretical analysis shows that modern catalysts allow, in principle, the thermochemical energy conversion with specific power loading (power density) w as high as 50–100 W per 1 cm^3 of catalyst [8]. Note that this value corresponds to the power density of the active zone of the modern nuclear reactors. However, to reach these very high w values it is necessary to provide an intensive heat supply into the catalyst bed. In an ordinary reactor/receiver, the light energy, first, is absorbed by a steel wall and then is transferred to the catalyst bed where it is converted to chemical energy. The sufficient thermal resistance between the wall and the catalyst bed together with the low thermal conductivity of the catalyst leads to a limitation of the heat flux by the values of about 4–9 W/cm^2 [6]. To minimize the limitation, one possible way is the direct heating of the catalyst with high-density light "from inside" in a reactor with the light-transparent walls. Because of the bulk character of the heating such reactors are named "volumetric" [2–4,9–12]. Note that in such reactors an additional enhancement of the reaction rate may be achieved due to a direct *photochemical* action of intense light flux.

In this paper we consider some peculiarities of high-temperature catalytic reforming of methane with steam

$$CH_4 + H_2O \leftrightarrow 3H_2 + CO \tag{1}$$

driven by concentrated light through transparent (quartz) and opaque (steel) walls. This system is compared with the similar one driven by high-power electron beam which penetrates inside the catalyst bed and provides its bulk heating. As the penetrating ability of the electron beam is higher than that of the light the effect of the catalyst bulk heating is more pronounced in that it has allowed to find out some additional peculiarities of radiation-driven endothermic catalytic reactions.

2. Experimental

The experimental setup being used for our study is based on a 10 kW Xenon lamp DKSShRb-10000 (former USSR) which is used as a source of an intense light flux (unit 10 in Fig. 1). The light is concentrated with a set of mirrors. The maximum output in the focal spot of the lamp is 1.2 kW of the radiation power. Flux density of the lamp can reach 200 W/cm^2 that is close to the power density typical for modern helioconcentrators [9,10,13].

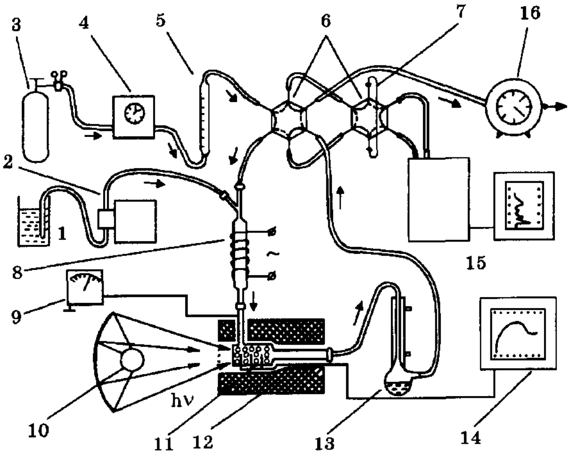
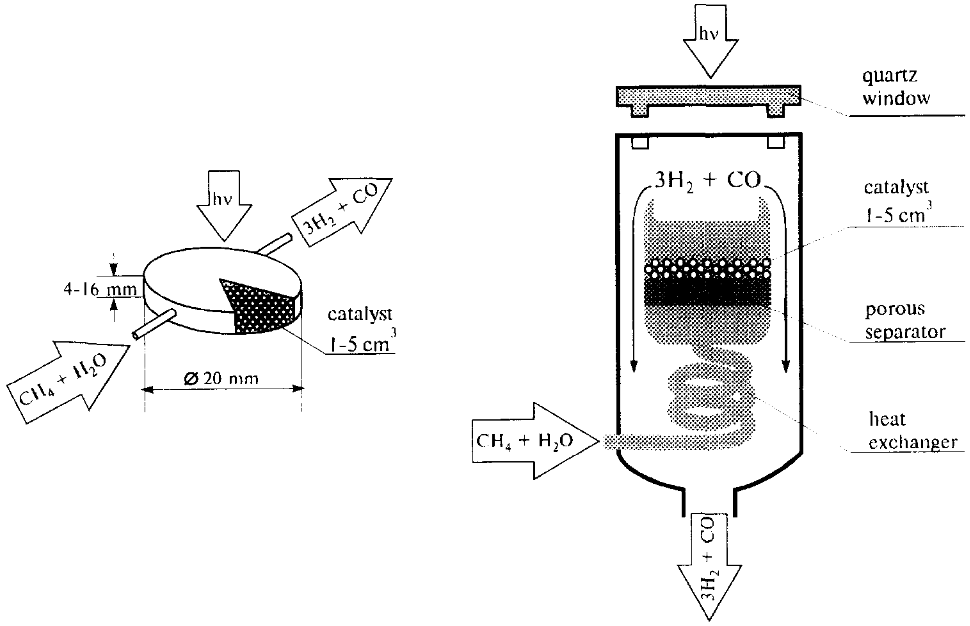


Fig. 1. Experimental setup used: 1 – water vessel; 2 – water pump; 3 – methane tank; 4 – gas flux adjustment unit; 5,16 – gas flow meter; 6 – gas flow communication unit; 7 – calibrated volume for chromatographic analysis; 8 – water evaporation unit; 9,14 – temperature recorders; 10 – 10 kW xenon lamp; 11 – catalytic reactor; 12 – thermoinsulation; 13 – water vapor condenser; 15 – gas chromatograph.



Reactor *A* **Reactor *B***

Fig. 2. Tested solar catalytic reactors with a quartz wall. The reactor A has a fixed bed of the catalyst; the reactor B allows fluidization of catalysts.

Two types of laboratory-scale light-transparent quartz reactors were constructed and tested (Fig. 2): a fixed bed reactor (type A) and a fluidized bed reactor (type B). To control the temperature of the reactor wall as well as that inside the catalyst bed we used a set of thermocouples. The distribution of the reactor surface temperature was found to follow the distribution of the incident radiation flux which was close to Gaussian.

The reactors were filled with commercial nickel-based catalysts GIAP-16, GIAP-3-6N (former USSR) and TH-2 (Poland) as well as K-3 (Ru-based), SNM-4 (Cu-based) and SA-1 (Fe-based) (all former USSR). Usually we used the catalyst fraction of 0.5–1.0 mm. The measurements were performed at steady-state conditions. The content of the dry gas mixture at the outlet of the reactor was recorded by a gas chromatograph.

A similar setup has been used for investigation of the electron beam action with a U-12M electron accelerator (energy of electrons=3 MeV) as a source of radiation. More experimental details may be found elsewhere [14–17].

3. Results and discussion

An important feature of our experiments is a non-isothermal condition of the energy conversion due to nonuniform absorption of radiation in the catalyst bed. For this reason it is difficult to compare thoroughly the kinetic peculiarities of a chemical process on the irradiated and nonirradiated catalyst [11,12]. Therefore, here we study the total effect of the radiation action due to an increase in the heat transfer inside the catalyst bed, enhancement of the reaction rate caused by photon (or electron) radiation, etc. With this aim we have compared the overall rate of the methane reforming in transparent (quartz) and nontransparent (steel) reactors of the same size under the same conditions.

The main characteristics of the process, namely, the specific rate of hydrogen production r, specific power loading w and efficiency η are calculated using the data on products composition and the standard thermodynamic tables [18]:

$$r = u\delta/100V, \qquad w = W_{\mathrm{chem}}/V,$$
$$\eta = W_{\mathrm{chem}}/W_{\mathrm{inc}} = wV/W_{\mathrm{inc}},$$

where W_{chem} is the enthalpy change during the energy accumulating reaction (per unit time), u is a volume rate of the gas mixture (without water vapor) at the outlet of the reactor at 20°C, V is the catalyst volume, and δ is the final content of hydrogen (vol%). We have investigated the dependencies of w and r upon the average power density of radiation $\rho = W_{inc}/V$, the conversion x of the main component, the nature of the catalyst and some other factors.

The experiments have shown that the intensification of heat supply leads to considerable reaction rate enhancement. The r and w values both in the quartz and steel reactors are measured to be as high as 30–40 N cm^3 H_2/s per 1 cm^3 of the catalyst and 75–95 W/cm^3, respectively, although in the quartz reactor it may be obtained at lower wall temperature and, consequently, with higher efficiency (Table 1) which is found to reach 50–75% at $x \approx 0.5$. The difference between the transparent and opaque reactors increases with the raise in the incident power and the thickness of the catalyst bed. For both reactors of 4 mm thick the values of w are rather close. For the 16 mm thick bed, the specific power loading in the quartz reactor is higher by the factor of 2.1. For the same conditions, the content of the products in both reactors are measured to be similar (typical contents are presented in Table 2), the main products being H_2, CO and CO_2. No additional substances have been detected in amount of more than 0.1 vol%.

The values of r and w appear to increase if the power supplied into the catalyst bed increases. For both transparent and nontransparent reactors the specific power loading of the light energy conversion increases linearly with the increase of ρ (Fig. 3(a)). The established linear dependence allows one to expect a further rise of w if the incident power increases. The specific power loading for the transparent wall reactor of 4–6 mm thick may reach 90–100 W/cm^3. At the constant incident power, the value of w decreases with an increase in the thickness of the catalyst bed, and for 16 mm thick transparent reactor is measured to be no larger than 35 W/cm^3.

The nonisothermal conditions of the process under study result in some specific experimental dependen-

Table 1
Reactor wall T_w and catalyst bed T_c temperatures as well as the efficiency η of the light-to-chemical energy conversion for the light transparent and opaque reactors (K-3 catalyst, $H_2O/CH_4=2.0\pm0.1$)

W_{inc} (W)	Thickness (mm)	Quartz reactor			Steel reactor		
		T_w (°C)	T_c (°C)	η (%)	T_w (°C)	T_c (°C)	η (%)
40	4	560	530	36	615	520	39
95	4	790	580	46	910	540	41
170	4	990	720	56	1170	685	47
120	8	825	640	74	940	545	62
145	8	890	680	69	1045	580	54
95	20	810	485	43	990	405	33
210	20	1060	520	57	—	460	42

Table 2
Some experimental results on methane steam reforming under heating of the K-3 catalyst by concentrated light ($H_2O/CH_4=2.0\pm0.1$)

Reactor	Thickness (mm)	W_{inc} (W)	τ (s)	Product content (vol%)			x	r (s^{-1})	w (W/cm^3)	η (%)
				H_2	CO	CO_2				
Quartz	4	95	0.024	62	8	7	0.47	21	44	46
Quartz	4	170	0.023	73	19	3	0.83	37	93	55
Quartz	16	170	0.046	67	15	4	0.61	15	36	51
Steel	4	160	0.024	68	19	2	0.67	33	79	49
Steel	16	170	0.072	61	7	9	0.44	8	17	25

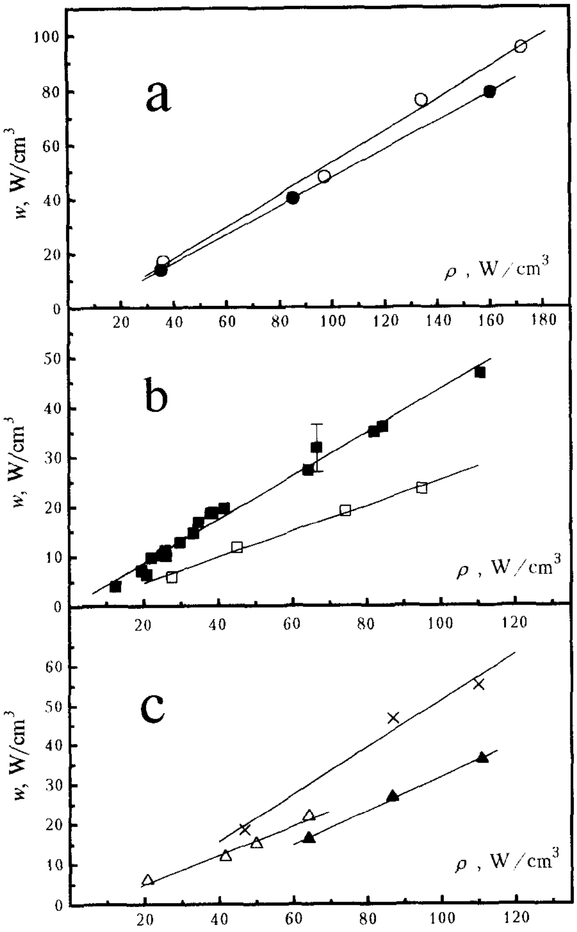


Fig. 3. Specific power loading w of radiation-to-chemical energy conversion vs. the power density ρ of incident radiation flux: (a) reaction (1) under light flux, the K-3 catalyst, $H_2O/CH_4=2.0\pm0.1$, reactor A of 4 mm thick, made of quartz (○) and steel (●); (b) reaction (1) under electron beam, $H_2O/CH_4=2.0\pm0.2$, ■ – the K-3 catalyst, □ – the GIAP-3-6N catalyst; (c) reactions (2) (△, ▲) and (3) (×) under electron beam ($H_2O/CH_3OH=1.0$, △, × – the K-3 catalyst, ▲ – the SNM-4 catalyst).

cies. For example, the functions of w, r and η on the methane conversion x have smooth maxims (Fig. 4(a)). At temperature 600–700°C the maximum rate of the hydrogen formation is reached in the light transparent reactor at $x=0.5$–0.6 that corresponds to the gas-residence time $\tau=2\times10^{-2}$–10×10^{-2} s. These dependencies are smoothed because of a compensation of the rise (or fall) of the catalytic reaction rate with decreasing (or increasing) depth of conversion x, due to a decrease (or increase) of the catalyst temperature.

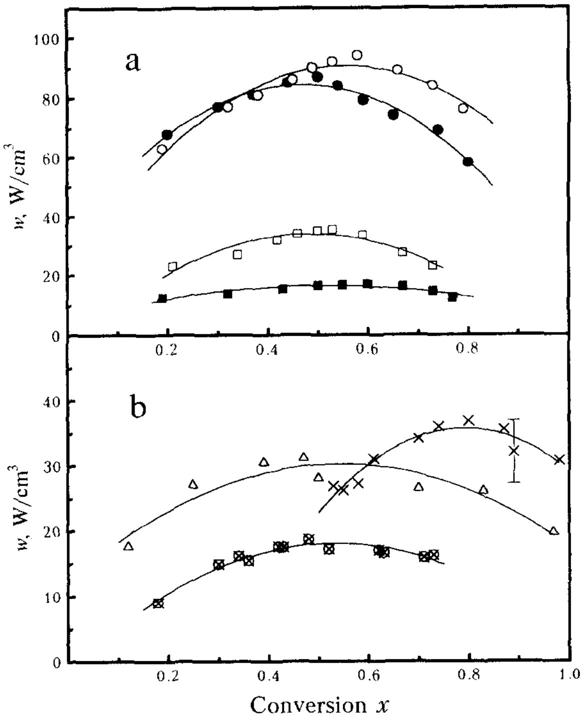


Fig. 4. Specific power loading w as a function of a key component conversion x: (a) reaction (1) under light flux, $W_{inc}=170$ W, catalytic reactor/receiver A of 4 mm (○ – quartz, ● – steel) and 16 mm (□ – quartz, ■ – steel) thick, the K-3 catalyst, $H_2O/CH_4=2.0\pm0.1$; (b) reactions (1) (⊗, $\rho=38$ W/cm³, the K-3 catalyst, $H_2O/CH_4=2.0\pm0.1$), (2) (×, $\rho=110$ W/cm³, the SNM-4 catalyst, $H_2O/CH_3OH=1.0$) and (3) (△, $\rho=70$ W/cm³, the K-3 catalyst) under electron beam.

Thus, direct irradiation of the catalyst allows to enhance considerably the rate of methane reforming by steam and to reach at $T\cong700$°C the specific power loading of the light-to-chemical energy conversion up to 100 W/cm³ that is close to the maximum possible values for the catalysts tested [6,8].

The increase observed can be analyzed in the frame of two different reaction mechanisms, namely, thermochemical and photochemical. For the first one, the chemical mechanism of the methane reforming is similar for the transparent and opaque reactors. In this case the rate enhancement in the quartz reactor is expected to be caused by an intensification of the heat supply inside the catalyst bed due to its direct irradiation (this effect is discussed above). For the second mechanism, the direct action of light can lead to initiation of a new reaction path due to a photochemical (or photocatalytic) activation of the system, that provides a raise of the reaction rate.

The main reason for the increase in the rate of the methane reforming found here is likely to be the thermochemical action of the concentrated light rather than the photochemical one. The thermal action results in more intensive heating of the catalyst almost "from inside" and in eliminating the discussed restrictions on heat supply into the catalyst bed. The predominant role of the thermochemical mechanism is collectively confirmed by the following experimental results:

1. the contents of the reforming products under both direct radiation and common heating are similar, no additional substances have been recorded (note: products of photochemical reactions may be decomposed at high temperature);
2. the low values of the reaction rate when irradiating only a pure support of the catalysts involved (namely, disperse Al_2O_3 without an active component);
3. the specific power loading in the quartz and steel reactors of a small thickness are close to each other and to the limiting heat-driven value for the given catalyst;
4. a distinct correlation between the rate of the reaction under light and activity of the catalyst used (for instance, the K-3 catalyst has a higher activity under both common and radiation heating than the GIAP-3-6N).

The reforming process under powerful electron beam, which also provides intense heat supply directly inside a catalyst bed, in many features is similar to the light-assisted process [14,15]. The rate of the hydrogen production is also extremely high and reaches 35 N cm^3/s per 1 cm^3 of the catalyst. Specific power loading w increases linearly with the increase of ρ (Fig. 3(b)) and may reach the value of 50 W/cm^3, which is close to the theoretical one [8]. The linear dependence $w(\rho)$ was previously predicted by a mathematical simulation of the methane steam reforming in a nonisothermal catalytic reactor with an intense volume heating [15]. Moreover, the same dependence takes place in the case of other endothermic reactions under electron beam (Fig. 3(c)):

$$CH_3OH + H_2O \leftrightarrow 3H_2 + CO_2, \tag{2}$$

$$2NH_3 \leftrightarrow N_2 + 3H_2. \tag{3}$$

The functions of the specific power loading on the reagent conversion x have smooth maxims at x=0.4–0.6, 0.5–0.8 and 0.5–0.6 for reactions (1),(2) and (3), respectively (Fig. 4(b)). All the data obtained indicate a predominant role of the thermal mechanism in the chemical action of intensive ionizing radiation. This statement is based on the findings similar to those we have mentioned above for the light-driven reforming of methane, namely, the similar contents of the reforming products; the low values of the reaction rate in the absence of a catalytically active metal; a distinct correlation between the rate of the reaction under irradiation and the thermally driven activity of the catalyst used.

High penetrating ability of accelerated electrons provides catalyst bulk heating over thicker layer than in the case of solar light. Using electron beam we can obtain more detailed information about high-temperature catalysis under intense radiation heating. It is found that, for the systems involved, there is a "threshold" effect in the chemical action of the radiation, consisting in a rapid increase of the values of r, w and η when the power supply ρ into the catalyst bed becomes larger than some "threshold" value ρ^*. For the methane reforming by steam this value is found to be equal to 5 W/cm^3 [14]. If $\rho>\rho^*$, the specific power loading w increases almost linearly with the increase of ρ (see Fig. 3). Such a linear dependence allows one to expect a further rise of w if the value of W_{inc} increases, the real limit for the value of w being determined mostly by a thermal stability of the catalysts used. Indeed, this rise of specific power loading is accompanied by an increase in the maximum temperature inside the catalyst bed (e.g. from 700–750°C at ρ=90–100 W/cm^3 to 900–1000°C at ρ=200 W/cm^3 [14]), so the thermal stability of the catalyst used must be rather advanced.

One should note that an important feature of our experiments is the nonisothermal condition of the energy conversion process, due to nonuniform absorption of the electron beam (or light) along the catalytic reactor. In the absence of reagents, the maximum temperature, T_m, inside the catalyst bed has appeared to exceed 1000°C, the difference from the minimum catalyst temperature inside the same bed being ca. 200–300°C. The flow of reagents diminishes the value of T_m and smoothes out the temperature profile. The profile of temperature $T(l)$ along the reactor (l is an appropriate coordinate) is defined by the energy balance between radiation heat supply, energy losses, and heat absorption due to catalytic reaction.

Some observed regularities of the process under study, for example, the smooth maxim of the function $w(x)$ (see Fig. 4), are appreciably driven by this nonisothermity. Indeed, if the depth of conversion is increased and approaches to unity, the rate of the heat removing reaction obviously has to be decreased and the specific power loading has also to be decreased. However, this decrease is compensated by keeping the heat balance inside the reactor, which results in a proper rise of the catalyst temperature. This temperature rise initiates an increase in the reaction rate (and, hence, in the value of w) that partially compensates the initial fall of the rate due to an increase in x.

If we use a less active catalyst, the temperature inside the catalyst bed is increased to compensate partially the lower activity of the catalyst. Thus, in principle, a less active but more thermally stable catalyst can operate better than a more active but less stable one. A similar compensation effect has also been found in the course of mathematical simulation of the energy conversion process in a nonisothermal catalytic reactor [15]. In spite of these compensation we have, however, recorded a correlation between the rate of reaction and the activity of catalysts used [14,15]. The higher the catalyst activity (if measured under common heating by heat transfer through a wall) the greater the reaction rate (specific power loading) under radiation.

The above experiments show that specific power loading of methane steam reforming is strongly influenced by the ratio m of the partial pressures of water vapor and methane at the reactor inlet. When m diminishes to its stoichiometric value ($m=1$) the rate of methane reforming is increased. It is well known that in the chemical industry the excess of vapor ($m\approx3$–6) is used in order to avoid coke formation. In our experiments, the coke formation appeared to be negligible at $m>1.5$. This probably indicates the elimination (or at least appreciable weakening) of the coke formation process under intensive heat supply into the catalyst bed. This lowering of the value of m saves a substantial amount of the energy needed for water evaporation and, hence, allows one to improve the energetic efficiency of energy conversion.

Another interesting feature of the radiation induced catalysis is that the high-rate of reactions (1)–(3) under intense ionizing radiation gives the possibility of rapidly adjusting the temperature of the catalyst bed. It is easy to estimate the typical time, t_c, of the catalyst cooling by $\Delta T=100°C$ via increasing the specific power loading by $\Delta w=10$–50 W/cm^3 caused, for example, by an increase of the reagents supply. This time is predicted to be $t_c\approx C\Delta T/\Delta w\approx1$–$10$ s, where $C=0.5$–1.0 J/(cm^3 K) is a typical volume heat capacity of the catalyst. Our experiments have confirmed this conclusion. For example, if we increase the rate of the reagents feeding, the catalyst temperature can drop rapidly ($t_c\approx10$ s) by 150–300°C [15].

Thus, we have found several common features of the endothermic catalytic reactions under direct irradiation of catalysts regardless of the reaction, catalyst or radiation nature. These are likely to result from intense, volumetric and nonisothermal character of the direct catalyst heating by radiation. As a confirmation of this statement one could consider our recent preliminary results on direct conversion of *microwave energy* into energy of chemical fuels [19], which in several features resemble the results reported above. Such a similarity looks quite reasonable since a microwave radiation may also penetrate into a catalyst bed thus providing its intense heating from "inside".

Note that on the basis of above experimental data on the direct radiation-driven high-temperature catalysis we have suggested an efficient thermocatalytic method for the nuclear-to-chemical energy conversion called ICAR-process (immediate catalytic accumulation of ionizing radiation energy) [15]. The main idea of the method is a combination of both nuclear and catalytic reactors in the same technological volume, by loading the catalyst directly into the active (energy releasing) zone of the nuclear reactor (Fig. 5). Two variations of the ICAR-process based on commercial or uranium-containing catalysts have been discussed [15,20]. A new type of particular UO_x-based catalysts for steam reforming of methane, which are able to simultaneously release energy via the uranium fission, has been recently synthesized and studied [21]. These special catalysts as well as conventional commercial catalysts being used in the ICAR method are shown to be capable of ensuring a considerable intensification of the energy-accumulating chemical reaction and of

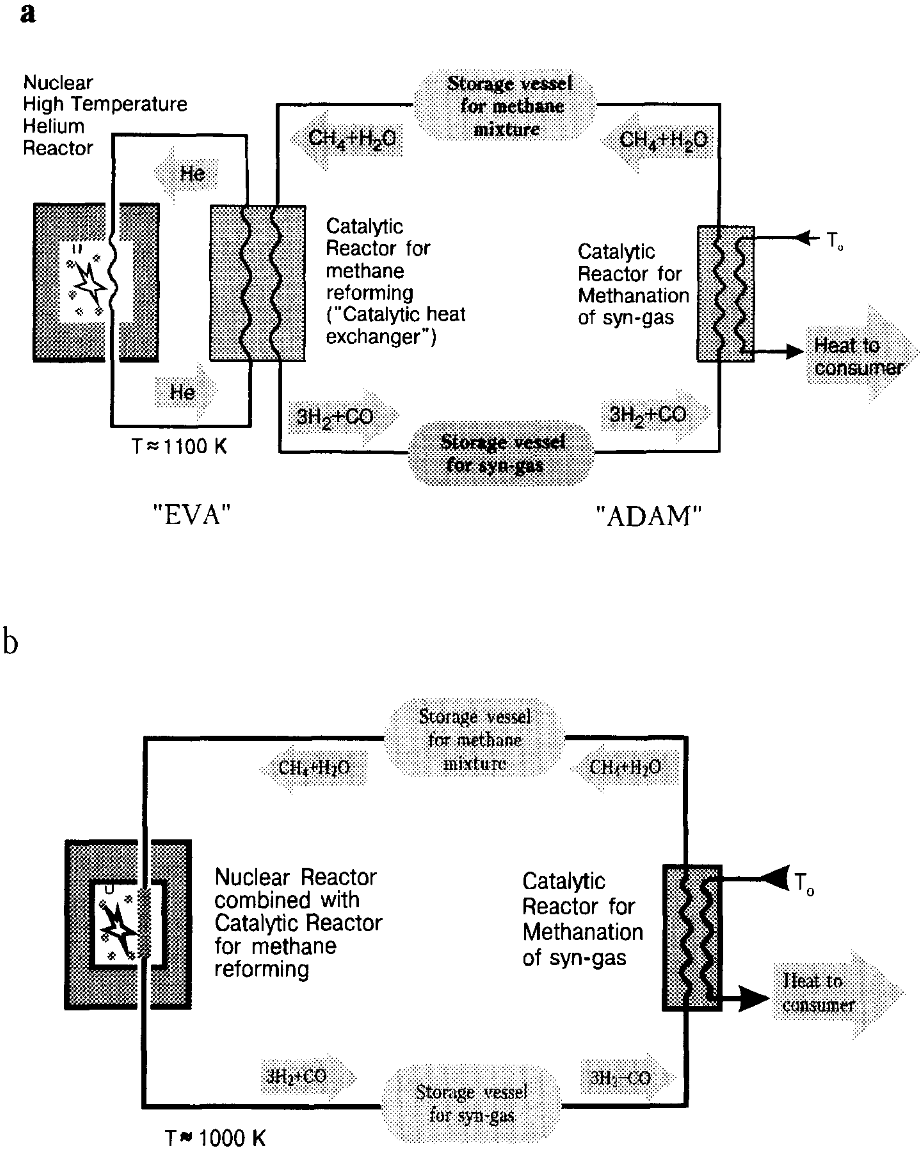


Fig. 5. Principal schemes of thermocatalytic nuclear-to-chemical energy conversion via reaction of methane steam reforming: (a) traditional EVA-ADAM scheme, involving the stage of heat transfer by an intermediate coolant (helium) from a nuclear reactor to a catalytic reactor; (b) new suggested ICAR scheme of direct nuclear-to-chemical energy conversion excluding this stage, due to combining the nuclear and catalytic reactors.

increasing the specific power loading of the energy conversion up to 100 MW/m^3.

One should mention as well, that the suggested radiation-thermocatalytic method of directly converting the energy of ionizing radiation into chemical energy could be beneficially applied without significant changes for devices based not only on nuclear fission processes. Very plausible areas of its application could be small- and moderate-scale energy-supplying devices based on well-known heat-evolving elements with some radioactive isotopes, as well as thermonuclear systems being under current development and based on the nuclear fusion process. It is very likely that the ICAR technology could be capable of removing and converting the enormous fluxes of ionizing radiation from the superheated zone of thermonuclear fusion reactors, thus protecting their internal walls [20]. No doubt, that the first commercialization of the ICAR technology method should be expected for small- or moderate-scale energy-supplying devices designed for some local, remote or autonomous consumers with strongly time-varied energy demands.

In our opinion, the thermocatalytic conversion of solar or ionizing radiation energy described in this article can be realized as one of the stages of useful electricity production with, respectively, high efficiency. It is of interest to mention that recently a new scheme of radiation-to-electricity energy accumulation based on a zero-emission turbine (ZET) has been suggested and analyzed [22,23]. We have concluded that the ZET-equipped thermochemical cycles may appear more efficient, compact and reliable for storing and releasing the energy than the often discussed systems on the base of water electrolysis (an intermediate step of accumulation of energy) with subsequent production of electricity with the use of highly efficient hydrogen–oxygen fuel cells. Indeed, in the case of the solar energy conversion and storage via photovoltaic devices the upper energy-converting efficiency of the whole "solar energy→useful electricity" path is expected no more than ca. 10% (this value is the product of 20% efficiency for the photovoltaic conversion of solar energy, 80% efficiency of a water electrolyzer, and 70% expected efficiency of a fuel cell). On the contrary, the direct thermochemical conversion of solar energy into the energy of chemical fuels can be accomplished with efficiency more than 40%, the expected overall efficiency of the cycle "solar energy→syn-gas (accumulation of energy)→ ZET-produced electricity" can be up to 20%. Moreover, no sophisticated and low power density equipment is needed in the latter case. A similar estimate for "nuclear energy→electricity (by steam turbines)→electrolysis of water→electricity (by fuel cells)" cycle gives ca. 17% of the overall efficiency (30%×80%×70%), while the direct conversion of nuclear energy into chemical energy, say, of a monofuel (syn-gas) via ICAR-process in combination with ZET could provide the overall efficiency more than 25%, because the energy accumulating efficiency of the ICAR-process can be more than 50%.

4. Conclusions

The above data evidence that application of a solar energy receiver/reactor with transparent walls allows an increase of both the specific power loading and the energetic efficiency of light-to-chemical energy conversion up to the values of 100 W/cm^3 and 75%, respectively. In such a reactor, the specific rate of hydrogen production can reach 40 normal cm^3 H_2/s per 1 cm^3 of the catalyst when using the common industrial catalysts of methane reforming by steam. The observed enhancement of the methane reforming rate is found to be achieved due to the thermochemical action of concentrated light rather than the photochemical one. The experiments have shown that neither the nature of an intense penetrating radiation nor the nature of an endothermic reaction used for carrying out the energy accumulation do need a sufficient influence on the main regularities of the energy conversion. Thus, the idea of intense volumetric heating of a catalyst from inside by direct action of electromagnetic radiation seems very attractive for application to concentrated solar light, powerful electron beams, nuclear fussion and microwaves.

The results presented witness that even in the near future one can expect development of highly efficient commercial volumetric receivers/reactors with transparent walls. This will result in creation of a new generation of very efficient and compact Solar Energy Converters based on catalytic processes.

References

[1] K.I. Zamaraev, V.N. Parmon (Eds.), Photocatalytic Solar Energy Conversion, Nauka, Novosibirsk, 1983 (in Russian).

[2] Proceedings of the Fifth International Symposium on Solar High-temperature Technologies, Davos, Switzerland, 1990, Solar ~~Energy Materials~~ and Solar Cells, Vol. 24, 1991, pp. 1–780.

[3] Proceedings of the Sixth International Symposium on Solar High-temperature Technologies, Almeria, Spain, 1992.

[4] Proceedings of the Seventh International Symposium on Solar Thermal Concentrating Technologies, Moscow, Russia, 1994.

[5] Yu.I. Aristov, V.N. Parmon, K.I. Zamaraev, Proceedings of the Second Soviet-Indian Seminar on Catalysis, Hyderabad, India, 1989, p. 590.

[6] Yu.I. Aristov, V.N. Parmon, Photocatalytic Solar Energy Conversion, Nauka, Novosibirsk, 1991, p. 257 (in Russian).

[7] V.I. Anikeev, V.N. Parmon, Yu.I. Aristov, V.I. Zheivot, V.A. Kirillov, K.I. Zamaraev, Dokl. Akad. Nauk SSSR 289 (1986) 158 (in Russian).
[8] Yu.I. Aristov, I.I. Bobrova, N.N. Bobrov, V.N. Parmon, Proceedings of the Seventh World Hydrogen Energy Conference, Moscow, Russia, 1989, Pergamon Press, New York, 1989, p. 1079.
[9] M. Posnansky, T. Pylkkanen, in: Ref. [2, p. 201].
[10] R. Buck, J.F. Muir, R.E. Hogan, R.D. Skocypec, in: Ref. [2, p. 499].
[11] C. Revilliod, A.J. McEvoy, M. Gratzel, in: Ref. [2, p. 522].
[12] K. Hunder, in: Ref. [2, p. 696].
[13] P.C. Klimas, R.B. Diver, J.M. Chavez, in: Ref. [2, p. 136].
[14] Yu.Yu. Tanashev, S.I. Prokopiev, Yu.I. Aristov, V.N. Parmon, Russ. J. Phys. Chem. 65 (1991) 1592 (in Russian).
[15] Yu.I. Aristov, Yu.Yu. Tanashev, S.I. Prokopiev, L.G. Gordeeva, V.N. Parmon, Int. J. Hydrogen Energy 18 (1993) 45.
[16] Yu.I. Aristov, A.I. Fixel, V.N. Parmon, Geliotechnika (1989) 51 (in Russian).
[17] Yu.I. Aristov, V.I. Fedoseev, V.N. Parmon, Int. J. Hydrogen Energy 22 (1997) 869.
[18] K.P. Mischenko, A.A. Ravdel (Eds.), Brief Guidebook of Physico-chemical Data, Khimia, Moscow, 1974 (in Russian).
[19] Yu.I. Aristov, V.I. Fedoseev, Yu.Yu. Tanashev, V.V. Pushkarev, V.N. Parmon, Proceedings of the 11th World Hydrogen Energy Conference, Stuttgart, Germany, 1996, p. 931.
[20] V.N. Parmon, Yu.I. Aristov, Ross. Khim. Zh. 37 (1993) 25 (in Russian).
[21] L.G. Gordeeva, Yu.I. Aristov, E.M. Moroz, N.A. Rudina, V.I. Zaikovskii, Yu.Yu. Tanashev, V.N. Parmon, J. Nucl. Mat. 218 (1995) 202.
[22] S.I. Prokopiev, Yu.I. Aristov, V.N. Parmon, Izvestiya RAS, Ser. Energetika (Power Engineering) /3 (1994) 70 (in Russian).
[23] S.I. Prokopiev, Yu.I. Aristov, V.N. Parmon, Proceedings of the 11th World Hydrogen Energy Conference, Stuttgart, Germany, 1996, p. 925.