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Molecular hydrogen production by radiolysis of water on the surface of nano-ZrO₂ under the influence of gamma rays

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ABSTRACT

In this research, the radiation-heterogeneous processes of water decomposition on the surface of zirconium dioxide nanoparticles (n-ZrO₂) were studied. The kinetics of buildup of molecular hydrogen during the radiolytic processes of water decomposition was also examined. The production of H₂ and H₂O₂ through water radiolysis was investigated to develop a computational model and disclose the kinetic behavior of water radiolysis. The enthalpy of ZrO₂ nanoparticles was studied at the temperature range T=1200-2900 K, in which ZrO₂ nanoparticles has a two-phase transition. Some of the electrons were transported to the surface of the nanoparticles during the physical and physicochemical stages of the process and emitted into the water. At the same time, the migration of energy carriers in radioactively active oxide compounds changed at different intervals depending on the composition, structural stability, and electro-physical properties of the oxides.

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KEYWORDS

Hydrogen generation
Nano zirconium oxide
Enthalpy
Water splitting
γ-radiation

1. Introduction

The radiolysis of water results in the production of electrons, atoms, radicals, ions and molecules due to ionizing radiation. A brief history of the development of the understanding of water radiolysis with a focus on the H₂ production has been published [1-2]. It was found that the energy carriers' migration in radiation-catalytic active oxides varies at different intervals depending on the oxides composition, their structural regularity and electrophysical characteristics. Therefore, the effective energy transfer distance in radiation-catalytic active oxides is limited by these interval dimensions, which in turn shows the radiation-catalytic activity, which again depends on the particle size [3-8].

Nano-ZrO₂ has good thermal insulation and dielectric properties over a wide temperature range, which allows it to be considered as a promising material in the field of microelectronics and the use of construction materials [9-14]. Nanostructure materials possess developed surfaces and increased defects on the boundary of particles, which are of remarkable significance in radiation-heterogeneous processes with their participation, and during the progression of highly

sensitive detectors of ionizing radiation [15-18]. Heating devices operate at fairly high temperatures, using nanoparticle ZrO₂ to ensure their high quality. However, when using nanoparticle ZrO₂ as a construction material, it is necessary to take into account the large number of phase transitions at high temperatures.

In this work, the amount of molecular hydrogen obtained from radiolysis processes by changing the amount of water (m=0.02, 0.04, 0.06, 0.08 and 0.10 g), its formation rate, and radiation-chemical emissions are studied in the nano-ZrO₂/H₂O systems with d=20-30 nm particle size under the impact of gamma rays (⁶⁰Co, D_γ=0.30 Gy/s, T=300 K).

2. Experimental

The nanosized zirconium dioxide with 99.9% purity, diameter of 20-30 nm, and density of 0.4-0.6 g/cm³ was purchased from SkySpring Nanomaterials, Inc., USA. The analysis of hydrogen was carried out using the Agilent-7890A chromatograph in the following mode: column: C-1010 P., 30 m×0.53 mm I.D. (25467), D.-TCD, F.-3

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ml/min, 20 Hz/0.01 min, $T(\text{head})=50\text{ }^{\circ}\text{C}$, $T(\text{d.})=230\text{ }^{\circ}\text{C}$, M.F.=0 ml/min, g. C.–Ar, oven: $50\text{ }^{\circ}\text{C}$ (7.0 min), $20\text{ }^{\circ}\text{C/min}$ to $230\text{ }^{\circ}\text{C}$, i.T.: $230\text{ }^{\circ}\text{C}$.

The radiation test was done employing the gamma ^{60}Co isotope source. The retained measurements rate of the source was $dD/dt=0.40\text{ Gy/s}$. The calculation of the radiation dosage in these frameworks was performed in comparison with the electron thickness [19–21].

3. Results and discussion

Initially, the enthalpy of nanoparticle ZrO_2 ($M=123.22\text{ g/mol}$) was considered in the temperature range $T=1200\text{--}2900\text{ K}$. It is known that nanoparticle ZrO_2 has a two-phase transition in the temperature range under study. In the phase transition region, samples should be kept under the study temperature for about 1 hour to ensure the phase transition of the entire mass of the substance. When measuring the enthalpy of nanoparticle ZrO_2 , it should be borne in mind that the samples undergo two structural transformations. When the samples are heated in the furnace above the transition temperature, the process of complete and partial conversion from one structure to another takes place, and when the samples fall into the calorimeter, a reverse transition is observed, resulting in heat dissipation during cooling. Thus, according to this method, the phase transitions are fixed during the cooling of the samples. The obtained results are shown in Fig. 1, where the average heat capacity varies with temperature. Experience has shown that the enthalpy creates three conditional temperature zones that differ in velocity: (I: $1200\text{--}1450\text{ K}$, II: $1450\text{--}2650\text{ K}$, III: $2650\text{--}2900\text{ K}$).

From this, we can conclude that the ZrO_2 nanoparticles have the structure of monoclinic in the first region, as a result of which it undergoes a complete tetragonal modification in the temperature range of region I. The change in the growth rate of enthalpy in the temperature range of region II is due to the polymorphic transformation of the tetragonal structure of ZrO_2 nanoparticles into a cubic structure. In this regard, when processing the obtained results, it should be noted that in the temperature range $T_I \leq T_{II} \leq T_{III}$ the ZrO_2 nanoparticles consist of a two-phase (monoclinic + tetragonal) state, which also depend on the temperature.

The experimental values of zirconium dioxide nanoparticles for

enthalpy over the entire temperature range are given by a single equation that takes into account the structure of the sample:

$$H_T - H_{298.15} = (1 - K_1) H^m(T) + K_1(1 - K_2) H^t(T) + K_2 H^c(T) \quad (1)$$

where $H^m(T)$, $H^t(T)$ and $H^c(T)$ are lines of enthalpy regressions for monoclinic, tetragonal and cubic modifications, respectively. The coefficients K_1 and K_2 (concentrations of tetragonal and cubic structures) have the following values:

- $K_1=0$ for monoclinic modification;

- $K_1=1$ for tetragonal and cubic modification;

- $K_1=[(T_1 - T_1^-)/(T_1 + T_1^-)]$ for solutions of monoclinic and tetragonal modifications;

- $K_2=1$ for cubic modification;

- $K_2=0$ for other modifications.

The heat capacity of monoclinic, tetragonal, and cubic modifications is given by the following equations, respectively:

$$C_p^m = a_0 + a_1 T + a_2 T^2 + a_3 \left[1/T^2 \right] \quad (2)$$

$$C_p^t = a_4 + a_1 T + a_5 T + a_6 T^2 \quad (3)$$

$$C_p^c = a_7 + a_8 T + a_9 T^2 \quad (4)$$

and taking into account (1), we obtain the following equation for the average heat capacity in the entire temperature range studied (5):

$$C_p = (1 - K_1) \left[a_0 + a_1(T + T_0)/2 + ((T^2 + T_0 T + T_0^2)/3 - a_3/T_0 T) \right] + K_1(1 - K_2) \left[a_4 + a_5(T + T_0)/2 + a_6(T_2 + T T_0 + T_0^2)/3 \right] + (1 - K_2) \left[a_4 + a_5(T + T_0)/2 + a_6(T^2 + T T_0 + T_0^2)/3 \right] \quad (5)$$

The coefficients of equation (5) were calculated by the least squares method. The obtained values show that at $T_1 + T_1^- = 9\text{ K}$ the transition from one structure to another takes place at the temperature $T_1 = 1450\text{ K}$. According to the calculations, the conversion from tetragonal modification to cubic modification takes place at $T_2 = 2660\text{ K}$ and the constants of Eq. 5 are presented below (cal/mol for enthalpy): $a_1 = 6.94045 \times 10$, $a_2 = 8.79621 \times 10^{-3}$, $a_3 = -1.43165 \times 10^6$, $a_4 = 7.52967 \times 10^1$, $a_5 = 3.55216 \times 10^{-3}$, $a_6 = 4.93324 \times 10$, $a_7 = 2.39006 \times 10^{-2}$ and variance of measurement results $S_0^2 = 0.589$.

The results of research in the temperature range $T=1200\text{--}2800\text{ K}$ allowed us to find the value of the heat of polymorphic transformations: $-5.5 \pm 1.5\text{ kcal/mol}$ and $-8.6 \pm 1.5\text{ kcal/mol}$, respectively 6.5% and 4.5% enthalpy size occurs at the transition point. The enthalpy of conversions from monoclinic to tetragonal, from tetragonal to cubic modification is 3.8 and 3.2 kcal/mol , respectively.

Fig. 2 shows the irradiation time (dose) dependencies of the content of molecular hydrogen achieved from radiation-heterogenous decomposition of nano-zirconia (with varying mass, $m=0.02, 0.04, 0.06, 0.08$ and 0.10 g) in the nano- ZrO_2 system (particle size $d=20\text{--}30\text{ nm}$) irradiated with gamma rays (^{60}Co , $D_1=0.30\text{ Gy/s}$, $T=300\text{ K}$).

As shown in Fig. 2, the speed of the process remains almost constant as the amount of nano- ZrO_2 increases. This again shows that the processes occur on the surface regardless of the amount of catalyst. In this way, the surfaces of oxides are charged emphatically and have an electron-acceptor characteristic [22–26].

The formation rate of molecular hydrogen was determined by water, nano- ZrO_2 , and overall system from linear parts of kinetic curves (Fig.

Fig. 1 Average heat capacity of zirconium dioxide versus temperature.

2) of studied (nano-ZrO₂/H₂O) systems. Molecular hydrogen formation rate obtained by radiolysis of nano-ZrO₂ was determined based on the Eq. 6:

$$w_0(H_2) = 0.01G_0(H_2)P = \frac{N_0(H_2)}{m_{ZrO_2}t} \quad (6)$$

Fig. 2 shows the formation rate of molecular hydrogen from the kinetic part of the curves according to the nano-ZrO₂ in the nano-ZrO₂/H₂O system.

$$w_{ZrO_2}(H_2) = \frac{N(H_2)}{m_{ZrO_2}t} \quad (7)$$

According to overall ZrO₂/H₂O system:

$$w_{tot}(H_2) = \frac{N(H_2)}{m_{tot}t} = \frac{N(H_2)}{(m_{H_2O} + m_{ZrO_2})t} \\ = \frac{m_{ZrO_2}}{m_{H_2O} + m_{ZrO_2}} \frac{N(H_2)}{m_{H_2O}t} = \frac{m_{ZrO_2}}{m_{H_2O} + m_{ZrO_2}} w_{ZrO_2}(H_2) \quad (8)$$

According to nano-ZrO₂, considering the $\Delta N(H_2) = N(H_2) - N_0(H_2)$ increase in molecular hydrogen with the addition of nano-ZrO₂ was determined using the following equation:

$$w_{ZrO_2}(H_2) = \frac{\Delta N(H_2)}{m_{ZrO_2}t} = \frac{N(H_2) - N_0(H_2)}{m_{ZrO_2}t} \quad (9)$$

If we multiply the numerator and denominator of Eq. 9 by m_{ZrO_2} , with simple transformations considering the Eq. 6 and 7:

$$w_{ZrO_2}(H_2) = \frac{m_{ZrO_2}}{m_{H_2O}} \frac{N(H_2) - N_0(H_2)}{m_{ZrO_2}t} = \frac{m_{ZrO_2}}{m_{H_2O}} \frac{N(H_2) - N_0(H_2)}{m_{ZrO_2}t} = \\ = \frac{m_{H_2O}}{m_{ZrO_2}} \left(\frac{N(H_2)}{m_{ZrO_2}t} - \frac{N_0(H_2)}{m_{ZrO_2}t} \right) = \frac{m_{H_2O}}{m_{ZrO_2}} [w_{ZrO_2}(H_2) - w_0(H_2)] \quad (10)$$

where, $G_0(H_2)=0.45$ molecule/(100 eV) is radiation-chemical yield of molecular hydrogen obtained from radiolysis of pure water and $N_0(H_2)$ and $N(H_2)$ is the content of molecular hydrogen obtained from pure water radiolysis and nano-ZrO₂/H₂O system, respectively.

Therefore, Compton scattering mainly occurs compared to other

processes (photoeffect, photonuclear reaction, electron-positron pair formation, etc.) in the ZrO₂, H₂O, ZrO₂/H₂O systems under the influence of $E_\gamma=1.25$ MeV (⁶⁰Co) energy of gamma rays. The energy of Compton electrons varies in the range of 0-1.02 eV based on the scattering angle. The Compton electrons, on the basis of their kinetic energy, pass from the nanoparticle into the liquid phase or vice versa several times, losing the kinetic energies gradually in both elastic and inelastic collisions and turning into thermal electrons in nano-zirconia/H₂O systems. In an inelastic collision in the physical phase (10^{-15} - 10^{-12} s) of the process: 1) electron (e^-)-hole ($ZrO_2^+(h^+)$) pair and excited electron of ZrO_2^* from molecules direct single ionization within nano-zirconia:

2) electron-ion (H_2O^+) pair and excited electron of H_2O^* from molecules direct single ionization in water:

Active intermediate, unbalanced energy carriers are formed during Eq. 11 and 12.

If the energy required to form an electron-hole pair inside ZrO₂ is under the impact of ionizing radiation (gamma rays, electrons) [21], then the radiation-chemical yield of the electron-hole pair is $G(h^+e^-)$, the radiation-chemical yield of the electron-excitation (exciton) states is equal to G_{exc} . These active intermediates (h^+ , H_2O^+ , e^- , ZrO_2^* , H_2O^*) play an important role in the process of achieving molecular hydrogen from the radiation-heterogeneous decomposition of water in the zirconia/H₂O system.

The holes generated inside the nanoparticle by ionizing radiation can be trapped by drift [22], part of which can be trapped by structural defects inside the particle, and another part can be transported to the particle surface and trapped by an adsorbed complex of water [$ZrO_2-H_2O_s$] on the surface and formed ion-complex as follow:

This ion-complex causes to electron-excitation of the complex by recombination with heat or tunneling electrons:

On the other hand, the excitons formed by ionizing radiation can be absorbed inside the nanoparticle and transmit their energy to a water complex adsorbed on the surface at a distance. In this case, the electronic-excitation of the complex is observed:

The energy of the short-lifetime electron-excitation complex [$ZrO_2-H_2O_s$]^{*} [23] is transferred to the adsorbed water molecule and causes its decomposition, resulting in the formation of intermediate products H^+ and OH^- :

In order to obtain H^+ and OH^- intermediate products from the decomposition of the water molecules, it is necessary to break the bond between them (E_{rab}). Therefore, the connection between the transmitted excitation energy (E_{exc}) and the communication energy must satisfy the $E_{exc} \geq E_{rab}$ condition.

The electrons radiated from the surface of the strong to fluid stage slowly lose their active vitality by versatile and inelastic collisions in

Fig. 2. Irradiation time (dose) dependencies of the content of molecular hydrogen achieved from radiation-heterogeneous decomposition of nano-zirconia (with varying mass, $m=0.02, 0.04, 0.06, 0.08$ and 0.10 g) in the nano-ZrO₂ system (particle size $d=20-30$ nm) irradiated with gamma rays (⁶⁰Co, $D_\gamma=0.30$ Gy/s, $T=300$ K).

water and initially changed over into warm electrons, and after that can rescue within the water [24-31]:

It has been proved both experimentally [25] and theoretically [26-31] in systems produced by suspension of nano-ZrO₂ in water that the radiation-chemical yield of salvaged electrons (Eq. 17) in the liquid phase is higher than in pure water, and this value varies depending on the size of the nanoparticles. The molecular hydrogen production during Eq. 18 and 19 by the radiolytic decomposition between water molecules and salvaged electrons (e_{aq}^-), as well as protonated water molecules (H₃O⁺) in the intergranular liquid phase, can be described as follows:

Here it becomes clear that one electron-hole pair or two excitons are used to obtain one molecule of hydrogen. Reactions 13-16, 21 play a major role in the molecular hydrogen production from the radiation-heterogeneous decomposition of water adsorbed on the nano-zirconia surface under the influence of gamma rays. However, the radiation-chemical yield of molecular hydrogen obtained from the decomposition of water was less than 0.38 molecules/(100 eV) in systems created by the adsorption of water on the surface of nano-ZrO₂ irradiated by gamma rays. This implies that the surface thickness of the vitality exchange centers on the surface of nano-ZrO₂ is exceptionally little. As a result, the radiation-chemical surrender of atomic hydrogen produced during reactions 18-21 increases too much.

4. Conclusions

The results of research in the temperature range T=1200-2800 K allowed to find the value of the heat of polymorphic transformations: -5.5±1.5 kcal/mol and -8.6±1.5 kcal/mol, respectively 6.5% and 4.5% enthalpy occurs at the transition point. The enthalpy of conversions from monoclinic to tetragonal, from tetragonal to cubic modification is 3.8 and 3.2 kcal/mol, respectively. It can be concluded that radiation-chemical yield of molecular hydrogen obtained by radiolysis processes with varying mass of the nano-ZrO₂ in the range of $m_{ZrO_2} = m = 0.02; 0.04, 0.06, 0.08$ and 0.10 g in nano-ZrO₂/H₂O systems (particle size- $d=20-30$ nm) irradiated with gamma rays (^{60}Co , $D_f=0.30$ Gy/s, $T=300K$) are as follow: if determined for nano-ZrO₂, the increase in $G(H_2)=0.38-2.98$ molecules/(100eV). Thus, in this way on the base of nanomaterials radiation-catalytic processes enable to transform ionizing radiation energy to chemical one with great efficiency. Nano size radiation-heterogeneous systems open new actual insight into radiation processes and radioactive study of materials. It is clear from the presented results that nanostructured materials become an important role in nuclear-power engineering as structural and functional materials practically in all stages of the nuclear fuel cycle. It is extremely important for the formation in nanostructured materials after exposure ordered nanostructure from the new phase with a period of a few

nanometers, promoting the preservation of the properties of materials under high irradiation.

References

- [1] I.M. Neklyudov, V.N. Voevodin, Modern status of radiation material science 10th International Conference, Interaction of radiation with a solid body. (2013) 127-130.
- [2] S. Le Caer, Water Radiolysis Influence of Oxide Surfaces on H₂ Production under Ionizing Radiation, Water. 3 (2011) 235-253. <https://doi.org/10.3390/w3010235>.
- [3] D. Meisel, Charge Carrier Transfer across the Silica Nanoparticle/Water Interface, J. Phys. Chem. 102 (1998) 7225–7230. <https://doi.org/10.1021/jp982129p>.
- [4] N.G. Petrik, A.B. Alexandrov, A.I. Vall, Interfacial Energy Transfer during Gamma Radiolysis of Water on the Surface of ZrO₂ and Some Other Oxides, J. Phys. Chem. 105 (2001) 5935-5944. <https://doi.org/10.1021/jp004440c>.
- [5] J.A. LaVerne, L. Tandon, H₂ Production in the Radiolysis of Water on UO₂ and Other Oxides J. Phys. Chem. 107 (2003) 13623–13628. <https://doi.org/10.1021/jp035381s>.
- [6] J.S. Southworth, S.P.K. Koehler, S.M. Pimblott, Gas Production from the Radiolysis of Water Adsorbed on ZnO Nanoparticles. J. Phys. Chem. 122 (2018) 25158-25164. <https://doi.org/10.1021/acs.jpcc.8b04276>.
- [7] S.C. Reiff, J.A. LaVerne. Radiation-Induced Chemical Changes to Iron Oxides. J. Phys. Chem. 119 (2015) (24) 7358-7365. <https://doi.org/10.1021/jp510943j>.
- [8] S.C. Reiff, J.A. LaVerne. Gamma and He Ion Radiolysis of Copper Oxides. J. Phys. Chem. 119 (2015) (16) 8821-8828. <https://doi.org/10.1021/acs.jpcc.5b02079>.
- [9] O. Roth, B. Dahlgren, J.A. LaVerne. Radiolysis of Water on ZrO₂ Nanoparticles. T J. Phys. Chem. 116 (2012) 17619-17624. <https://doi.org/10.1021/jp304237c>.
- [10] J.A. LaVerne,, Lav Tandon, H₂ and Cl₂ Production in the Radiolysis of Calcium and Magnesium Chlorides and Hydroxides. J. Phys. Chem. 109 (2005) 2861-2865. <https://doi.org/10.1021/jp044166o>.
- [11] A.A. Garibov, T.N. Agaev, G.T. Imanova, S.Z. Melikova, N.N. Gadzhieva IR spectroscopy study of the radiation-thermal decomposition of water on nanosized zirconium dioxide, High energy chem. 48 (2014) 239-243. <https://doi.org/10.1134/S0018143914030059>.
- [12] T.N. Agaev, A.A. Garibov, S.Z. Melikova, G.T. Imanova, Radiation-Induced Heterogeneous Processes of Water Decomposition in the Presence of Mixtures of Silica and Zirconia Nanoparticles, High Energy Chem. 52 (2018) 145–151. <https://doi.org/10.1134/S0018143918020029>.
- [13] A.A. Garibov, T.N. Agaev, S.Z. Melikova, G.T. Imanova, Radiation and catalytic properties of the n-ZrO₂–n-Al₂O₃ systems in the process of hydrogen production from water, Nanotechnol. Russ. 12 (2017) 252–257. <https://doi.org/10.1134/S1995078017030077>.
- [14] M. Kaya, G.T. Imanova, High Efficiency Biomass-Based Metal-Free Catalyst as a Promising Supercapacitor Electrode for Energy Storage (2021). <https://doi.org/10.2139/ssrn.3908407>.
- [15] G.T. Imanova, T.N. Agayev, S.H. Jabarov, Investigation Of Nano-ZrO₂ By The Methods Of X-Ray Phase, Scanned Electronic Microscope And Differential Thermal Analysis, Transactions of Azerbaijan National Academy of Sciences Physics and Astronomy. 2 (2020) 111-117.
- [16] B.H. Milosavljevic, S.M. Pimblott, D. Meisel. Yields and Migration Distances of Reducing Equivalents in the Radiolysis of Silica Nanoparticles. J. Phys. Chem. 108 (2004) 6996-7001. <https://doi.org/10.1021/jp049760c>.
- [17] A.K. Pikaev, Dosimetry and Radiation Chemistry, M., Nauka, (1975).

- [18] G.T. Imanova, T.N. Agayev, S.H. Jabarov, Investigation of structural and optical properties of zirconia nanoparticles by radiation-thermal and thermal methods, *Mod. Phys. Lett.* 35 (2021) 2150050. <https://doi.org/10.1142/S0217984921500500>.
- [19] J.F. Sauvage, A. Flinders, A.J. Spivack, R. Pockalny, A.G. Dunlea, C.H. Anderson, D.C. Smith, R.W. Murray, S. D'Hondt, The contribution of water radiolysis to marine sedimentary life, *Nat. Commun.* 12 (2021). <https://doi.org/10.1038/s41467-021-21218-z>.
- [20] M. O'Leary, A. Baidak, M. Barnes, T. Donocliot, C. Emerson, C. Figueira, O. Fox, A. Kleppe, A. McCulloch, D. Messer, R. Orr, F. Currell, First observation of radiolytic bubble formation in unstirred nano-powder sludges and a consistent model thereof, *Scientific Reports* 11 (2021). <https://doi.org/10.1038/s41598-021-01868-1>.
- [21] I. Ali, G.T. Imanova, X.Y. Mbianda, O.M.L. Alharbi, Role of the radiations in water splitting for hydrogen generation, *Sustain. Energy Technol. Assess.* 51 (2022) 101926. <https://doi.org/10.1016/j.seta.2021.101926>.
- [22] I. Ali, G.T. Imanova, A.A. Garibov, T.N. Agayev, S.H. Jabarov, A.S.A. Almalki, A. Alsubaie, Gamma rays mediated water splitting on nano-ZrO₂ surface: Kinetics of molecular hydrogen formation, *Radiat. Phys. Chem.* 183 (2021) 109431. <https://doi.org/10.1016/j.radphyschem.2021.109431>.
- [23] J. McGrady, S. Yamashita, S. Kano, H. Yang, A. Kimura, H. Abe, H₂ generation at metal oxide particle surfaces under γ -radiation in water, *J. Nucl. Sci. Technol.* 58 (2021) 604-609. <https://doi.org/10.1080/00223131.2020.1847705>.
- [24] M-C. Pignié, V. Shcherbakov, T. Charpentier, M. Moskura, C. Carteret, S. Denisov, M. Mostafavi, A. Thill, S. Le Caër, Confined water radiolysis in aluminosilicate nanotubes: the importance of charge separation effects, *Nanoscale*. 13 (2021) 3092-3105. <https://doi.org/10.1039/D0NR08948F>.
- [25] A. Kojima, K. Takayanagi, R. Taniguchi, S. Okuda, S. Seino, T.A. Yamamoto, Hydrogen Gas Generation from the Water by Gamma-Ray Radiolysis with Pre-Irradiated Silica Nanoparticles Dispersing, *J. Nucl. Sci. Technol.* 43 (2006) 1287-1288. <https://doi.org/10.1080/18811248.2006.9711222>.
- [26] G.T. Imanova, S.H. Hasanov, Observation the initial radiation to the surface of mixed nano catalyst on oxidation processes, *Int. J. Sci. Eng. Res.* (2020) 869-873.
- [27] G.T. Imanova, Kinetics of Radiation-Heterogeneous and Catalytic Processes of Water In The Presence Of Zirconia Nanoparticles, *Adv. Phys. Res.* (2020) 94-101.
- [28] G.T. Imanova, T.N. Agayev, A.A. Garibov, S.Z. Melikova, S.H. Jabarov, H.V. Akhundzada, Radiation-thermocatalytic and thermocatalytic properties of n-ZrO₂-n-SiO₂ systems in the process of obtaining hydrogen from water at different temperatures, *J. Mol. Struct.* (2021) 130651. <https://doi.org/10.1016/j.molstruc.2021.130651>.
- [29] G.T. Imanova, Gamma Rays Mediated Hydrogen Generation By Water Decomposition On Nano-ZrO₂ Surface, *MAMS*. (2021) 508-514. <https://doi.org/10.32474/MAMS.2021.04.000186>.
- [30] T.N. Agayev, S.Z. Musayeva, G.T. Imanova, Studying the Kinetics of formation of molecular hydrogen during the radiolysis of hexane and a mixture of C₆H₁₄-H₂O on a surface of n-ZrO₂, *Russ. J. Phys. Chem.* 95 (2021) 270-272. <https://doi.org/10.1134/S0036024421020023>.
- [31] G.T. Imanova, M. Kaya, Importance of the Radiations in Radiolysis Processes for Hydrogen Generation, *Generis publishing*. (2021).