APPLICATION OF METHODS OF MATHEMATICAL MODELING FOR DETERMINING OF RADIATION-PROTECTIVE CHARACTERISTICS OF POLYSTYRENE-METAL COMPOSITE MATERIALS

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Radiation safety features of polystyrene steel composite materials were found by means of mathematical modeling techniques. We determined the attenuation of the gamma quantum flux passing through a solid protective layer compared with those attenuation for the bulk protective layer. Change of fractional attenuation of the dose absorbed by 10 and 50 mm thick composites is calculated. Dependence between protective properties of composite and its blend composition was studied. Modifications of technical process of composite materials production were performed. Rotation speed of agitator system was found. It was defined that heating time of polystyrene steel mix is longer than heating time of polystyrene tungstic one. Degree of mix heating and integrity of thermic field on its surface was controlled with the help of IR radiometry methods.

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INTRODUCTION

One of the conditions of safe operation of nuclear facilities is effective functioning of all systems and elements of radiation protection. By creating radiation protection facilities, radiation-absorbing materials are implemented. At the present time, a significant number radiation protection materials with different properties are developed and used.

Concept of modern protective materials includes their multipurpose function. It includes: main characteristics (radiation protection) and additional properties raising from conditions of materials operation.

Creation of new types of radiation protection materials is based on combining materials with the most necessary properties. The obtained composites have a row of characteristics that base materials do not have.

Composite materials made of polystyrene reinforced with powdered aluminum [1 - 3] were developed. Different protective properties were implemented for increasing protective properties. Finding radiation protection characteristics was performed by means of numerical count [4 - 6]. Use of these methods was studied in this work.

Objective of this work is calculation of radiation protection characteristics of polystyrene metal composite materials, studying effectiveness of attenuation gamma quantum flow for composite materials with different mass profile of components and determination of optimal composite component proportions.

MAIN PART

By solving the issue of protection from ionization radiation it is necessary to solve the issue of protection from alpha and beta particles flaxes, neutron flux and gammas radiation. Maximum protection from neutrons is reached by using light elements (B, H, N) having large cross-sections of absorption. We considered protective materials used for protection from gamma and X-ray radiation. In this case implementation of elements with large atomic weight (Pb, W).

Development of radiation protection composite materials of different composition was performed. Polystyrene metal composites were proposed. By production of composites polystyrene was reinforced with powdered aluminum. This procedure allows obtaining base with high duty since polystyrene moistens aluminum well. In works [1, 2, 7, 8] composite materials where base of composite was filled with radiation protection additive agent. As additive agent powdered tungsten was used. Protective material is produced in the form of balls with 2 and 5 mm diameter. This allows fulfillment of filling out protective layer. Use of protection layer as balls give possibility to fill out the whole volume of protection, to make complex protective structures. Protective layer also has higher flexibility.

Composite materials were produced at KUASY 1400/250 thermoplastic apparatus. This equipment allows production of multicomponent reinforced products of thermostatic polymers. Since in our case components are mixed in a tank of preliminary heating, we had to install additional heating equipment. Control of mix heating uniformity and uniformity of components mixing was performed by Ti-814 [2, 7, 9] thermovisor. It is sensitive at 0.08°C. It is enough for fixation and defining nonuniformity of temperature field distribution on mix surface.

Characteristics of hardness and thermal conductivity of received composite were studied [10]. Lowering of thermal current for composite material used in the form of balls in comparison to solid ones is shown. Thermal properties get worse with decreasing of polystyrene component composite in the composition. Thermal conductivity of material also depends on proportion of different kinds of metal component in composite composition. Thermal properties get worse by increasing of aluminum component. Thermal properties hardly depend on size of metal component grains. In our case aluminum grains have size of 10…20 and 30…40 μm. Tungsten grains size was: 30…40, 60…80, 180…210 μm. By studying polystyrene metal composite materials hardness values were found. It is shown that hardness of materials depends on quantity of metal component and size of separate grains. Hardness increases with increasing metal additive agent. However, in case of significant decrease of polystyrene component strength of balls can lower. Hardness also increases with increase of grain size.

In works [1, 2, 7, 8] radiation protection properties of composites with tungsten additive agent were studied. Results were received by means of mathematical model approach. Interaction processes of radiation with substance were performed with the help of program package.

Primary development of this package is provided in work [4], further development – in works [5, 6].

Radiation protection characteristics of composite materials made in the form of solid layer and in the form of balls are received. Protective properties for composite layer in the form of balls decrease in proportion to the degree of protection layer filling. Numeric data received are well agreed with experimental results [3, 11].

Simulation was performed for different kinds of polystyrene metal composite materials. Performance of numeric modeling allowed defining gamma energies what are available during their full absorption. Areas of half attenuation of the dose absorbed. All calculations were made for protection layer 10 mm thick. This thickness of protection layer is defined by its use in individual protection sets. Individual protection complexes are used for wearing by service personal. That is why they do not have limitations for weight and thickness of protection layer.

Based on dependence of received absorption properties optimal compositions of component composite materials were defined. Materials with maximum absorption properties were found, but they have significant weight. Analysis of proportion of material weight and its radiation protection properties was conducted. According to it C080403, C080304, C080601 composite materials suit for individual protection sets. They contain 53% of polystyrene volume and 47% of metal component volume. This quantity of polystyrene allows full covering of metal grains. This way maximum hardness of material is gained. Tungsten amount varies from 20% to 45% of volume which provides opportunity to receive high radiation protection performances.

The second material used as radiation protection addition was St3sp steel. Production technology of composite material with addition of powdered steel differs from technology of composites with tungsten addition. Differences are connected with size of steel particles, its form. Size of particles is 180…210 μm. They had rectangular shape. Weight is lower that weight of tungsten. In case of lower weight it is necessary to decrease speed of rotation to 20 revolutions. The following modification was time of mix heating. Thermal production of tungsten is 155 W/m·K. Thermal production of St3sp steel is 48 …52 W/m·K which is three times lower than that of tungsten.

Accordingly it is necessary to select temperature modes, speed of mix feed. We should notice that it is necessary to conduct selection of operation modes (rotation speed, heating time, interval of component feed) for each kind of composite.

By its radiation protection properties these composites have lower characteristics than composites with tungsten. Study of absorbed dose change for certain kinds with component steel was performed in works [2, 8, 10]. It was found out that in case protective layer thickness is 10 mm only gammas with energy up to 10 keV are absorbed. However by some characteristics these composites differ in a better way in compared to composites containing tungsten. Since thermal conductivity of steel is three times lower than thermal conductivity of tungsten, thermal conductivity of composition material is also lower. Steel particles have shape of rectangular blocks (sphere tungsten particles) and that is why hardness and strength of composites is higher [10]. Taking this into account we can define the protective structures where these composites are the most effective. It was defined that this are fixed protective structures.

Use of granular filling allows significant reduction of construction period of protection structures. There appears possibility of quick change of shape, size and location. If necessary granular filling allows dismantling.

Use of granular filling allows creation of temporary structures that will provide opportunity to increase safety by repair works, maintenance, accident recovery operations.

RESEARCH AND DISCUSSION OF THE RESULTS

By production of polystyrene metal composite materials with addition of steel polystyrene (PSM-115), powdered aluminum (TU 1791-99-024-99), St3sp powdered steel were used. Size of aluminum particles is 30…40 μm, of steel particles – 180…210 μm. These particles are evenly distributed over composite amount. Steel particles had rectangular shape. Distribution of particles was chaotic. There is no selected direction of particles by composite. Cross-section of Fe080601 composite material is presented in Fig. 1.

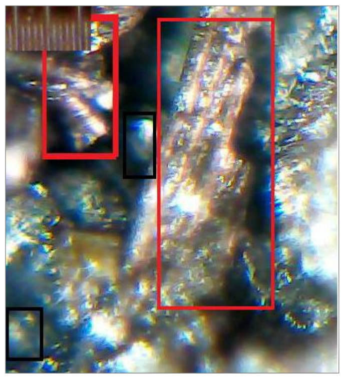

Fig. 1. Structure of composite material Fe080601

We can see composite structure in Fig. 1. Steel participles are marked with red markers (rectangles). Aluminum particles are marked with black markers. They have shape close to spherical one. They are also located randomly. Polystyrene has dark color. It fills out space between particles. This kind of polystyrene and metal components distribution provides possibility to consider composite material as homogenous material with reduced density.

Interaction processes of radiation current with a layer of protective substance were performed my means of Geant 4 v4.9.6p04 [6] program package. Results received by means numeral calculation are close to experimental data. One of parameters taken into account in process of modeling is density of protective material. We use definition of reduced density including weight of all components. Therefore it is necessary to receive material with maximum possible even distribution of all components over its amount. In our case, it is confirmed from the picture presented in Fig. 1. You can see from the figure that one of particles is turned to cross-section surface with its side surface, the second one with its end surface. It confirms their chaotic arrangement inside of composite.

By calculations different densities of protection material were considered. The second parameter is energy of grammas. Grammas with energies up to 1.5 MeV were considered. Composites of various thickness were also studied.

Since by calculations composite weight is one of parameters, we will present weight composition of these composites in Table.

Mass components of composite materials (PS-Fe-Al)

Material	Polystyrene (PS) mas. %	Steel (Fe+), mas. %	Aluminum (Al), mas. %
Fe100401	24.37	69.65	5.98
Fe100104	37.09	26.50	36.41
Fe080403	18.20	65.04	16.76
Fe080601	15.00	80.40	4.60
Fe080106	26.78	23.92	49.30
Fe050505	9.43	67.41	23.16
Fe050109	14.60	20.87	64.52
Fe050901	6.97	89.61	3.42

After calculations we receive attenuation curve of dose absorption depending on energy of grammas, component composition of composites and their structure. Analysis of received curves allows selection of suitable radiation protection composite for each concrete case.

Tissue-mimicking phantom located after protection layer is used as a target. Protection layer can have different structure (solid, filled with balls), different dimensions. We define absorbing characteristics of protection layer by value of relative decrease of absorbed dose of gamma radiation

$$Q = \frac{(D_{air} - D)}{D_{air}},$$

where Q – relative decrease of absorbed dose; D_{air} – estimated dose absorbed by tissue-mimicking phantom in the air without protective layer; D – estimated dose received by phantom located after protection layer.

Results of numerical modeling were presented on Figs. 2-4. At first, protection layers that had thickness of 10 mm were considered. Selection of this size was due to the fact that composite materials were used in NDC kits. Fig. 2 presents diagrams for composite materials with addition of iron.

Result of composite materials study of two kinds are presented. Attenuation of absorbed dose was considered depending on material composition. Protection layer was made of solid composite material and of balls. Size of balls is 2 mm. Lines with markers without filling mark absorbing properties of solid composite materials. Lines with painted markers mark materials made in the shape of balls. Materials differ by subgroups significantly. Effectiveness of gamma radiation absorption is higher for solid material. So, with gamma energy of 80 keV solid protection layer absorbs 80% gammas. And layer made of the same material, but in the shape of balls – 60%. This principle also works for other kinds of composite materials.

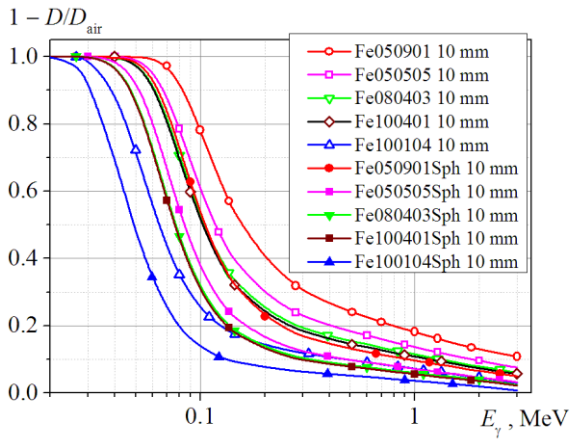

Fig. 2. Change the relative weakening of the absorbed dose of gamma radiation of different composites, depending on the energy of the gamma-rays. (Composite material of 10 mm thickness)

As for case with composite with tungsten component [7], radiation absorption properties depend on quantity of heavy metal components. In our case on steel. Absorption curves of composites with large content of steel that is higher than those having a little of block component. Effectiveness of gamma absorption does not depend much on amount of aluminum component and slightly depends on polystyrene component. It is confirmed by curves corresponding to Fe080403 (marker – triangle upside down) and Fe100401 (marker – rhombus) composites. Both these composites have similar amount of steel component. They differ by polystyrene and aluminum component. Fe080403 composite contains more aluminum in 2/15 of volume part and less polystyrene in 2/15 of volume part than Fe100401 composite. Insignificant difference of curves is observed with gamma energies of less than 60 keV. This principle works for solid protection as well as for protection with granular filling. For composite materials made in the shape of balls gammas with energy of 50 keV are well absorbed. Then radiation protection characteristics worsen rapidly. And at 122 keV (^{57}Co) line there is a half absorption. A significant amount of medical and research devices operates in this range of energies. Therefore, protection layer which is 10 mm thick and is made in the shape of balls for composite with steel component cannot ensure enough protection from ionization radiation. At energy of gammas of 1 MeV dose rate decreases no less than by 10%. Also, no more than 2% of 1.33 MeV (^{60}Co) radiation line is absorbed.

Composite materials with steel component can be used by creation of temporal protection structures. Their range of application is wider. Use of thicker composite material is possible. It was proposed to consider protection layer with thickness of 50 mm. Comparison of radiation protection properties of 10 and 50 mm thick composites was performed by mean of numerical approaches. Results of numerical modeling were presented in Fig. 3.

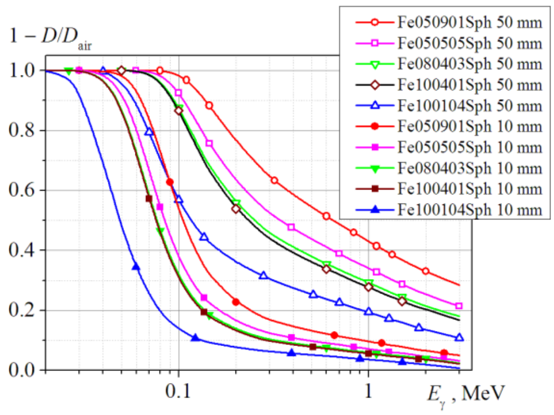

Fig. 3. Change the relative weakening of the absorbed dose of gamma radiation of different composites, depending on the energy of the gamma-rays. (Composite material of 10 and 50 mm thickness)

It is seen from Fig. 3 that effectiveness of composite material with 50 mm thick protection layer is significantly higher than for 10 mm thick materials. All curves are united into two groups by their form. Fe100104 composite having the lowest values stands separately. It is connected with little amount of steel component and with maximum amount of aluminum and polystyrene components. Composites (50 mm) have soft attenuation of protective properties. At 100 keV energy from 95 to 98% of falling gammas are absorbed. Accordingly, at 122 keV (^{57}Co) – from 90 to 95%. Half attenuation of dose is within energy interval of 300…700 keV gammas. 50 mm thick protection layer allows getting rid of gamma radiations of most domestic and industrial gauges. However, for high intensity radiation sources (^{60}Co) with 1.33 MeV line more than 20% of primary current of gammas is absorbed.

For the case when thickness of protection layer is 50 mm, structure of protection layer is balls, mathematical modeling of absorbing properties depending on composition of composite material was performed. Results of numerical calculation are presented in Fig. 4.

Using curves stated in Fig. 4 we will conduct analysis of gamma current attenuation effectiveness. Fe050901 composite has maximum absorbing properties. It contains nine volume parts of steel. The following group is curves corresponding with Fe080601 and Fe050505 composites containing 6 and 5 parts of steel. Then Fe080403, Fe100401 composites follow. The have the same composition of steel component, but Fe080403 composite has two more aluminum parts than Fe100401 composite. Therefore, its radiation protection properties are 1.5% higher. All composites of this group attenuate dose of gammas by 90…98% with 100 keV energies. Also from 80 to 97% of 122 keV (^{57}Co) line are absorbed.

With increase of gamma energy absorption effectiveness gets worse. Since half attenuation in case of 210 keV energy is typical of Fe080403, Fe100401 composites. Fe080601 and Fe050505 composites have 50% attenuation in case of 400 keV energy. And maximum characteristics for Fe050901 composite are 800 keV. In case, gamma energy value is 1 MeV, attenuation is from 30 to 40% of primary current intensity.

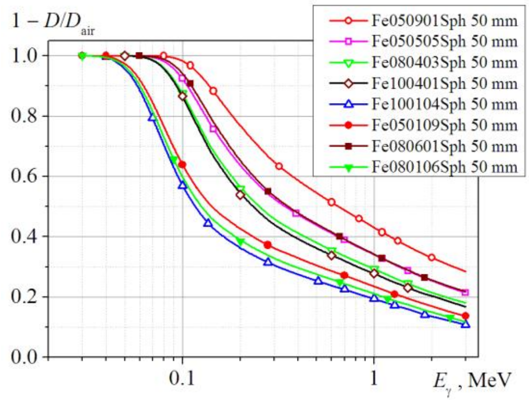

Fig. 4. Change the relative weakening of the absorbed dose of gamma radiation of different composites, depending on the energy of the gamma-rays. (The composite material of 50 mm thickness)

Fe050109, Fe080106, Fe100104 composites have the most low values of protection. They contain only one volume part of steel. It is seen from Fig. 4 that their characteristics slightly differ. Attenuation is in proportion to the amount of aluminum component. Half attenuation of these composite materials arises in case of 120 keV gamma energy. I.e., at the energy of 122 keV (^{57}Co) line. Therefore, use of composite materials of this group is effective only in the field of low (up to 80 keV) flow of gammas.

When selecting required composite material it is necessary to take into account its different physical characteristics. In works [7 - 10], there are dependences of hardness, thermal conductivity of composite materials. Based on these data we can conclude that Fe080601, Fe080403, Fe100401 are the most suitable for NDC kits. Fe050901 and Fe050505 composites have maximum radiation protection properties. However, their production is the most difficult and expensive. Therewith, because of large amount of metal component they have the lowest hardness values. The most effective use of them is in construction structures, addition to concrete. Fe080106, Fe100104 composites are easy to make, they have high strength, mobility properties. Therefore, they can be used in fixed protection structures where there are no limitations for size and weight of protection layer.

Performance of works on mathematical modeling of absorption processes of ionization radiation provides opportunity to define suitability of composite material and its main characteristics. After analysis of alteration curves in regards to attenuation of absorbed dose of gamma radiation, we can select kind of required composite.

CONCLUSIONS

1. By means of numerical methods values of relative attenuation of absorbed gamma radiation dose with use of polystyrene metal composites were obtained.

2. We analyzed the radiation protection properties of composite materials with steel component (PS-Fe-Al). Absorbing characteristics for three groups of compo-site materials with steel component were studied. Grouping was performed by the amount of metal polystyrene component.

3. Compositions of polystyrene and steel composite materials having maximum absorbing properties were found.

4. It is demonstrated that Fe080601, Fe100401 composites are the most effective in use of NDC kits.

5. For polystyrene and metal composites with addition of steel (PS-Fe-Al) improvement of their production technology was performed.

6. Modification of IR radiometric heating diagnostics methods was performed.

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ПРИМЕНЕНИЕ МЕТОДОВ МАТЕМАТИЧЕСКОГО МОДЕЛИРОВАНИЯ ДЛЯ НАХОЖДЕНИЯ РАДИАЦИОННО-ЗАЩИТНЫХ ХАРАКТЕРИСТИК ПОЛИСТИРОЛ-МЕТАЛЛИЧЕСКИХ КОМПОЗИЦИОННЫХ МАТЕРИАЛОВ

В.Ф. Клепиков, Е.М. Прохоренко, В.В. Литвиненко, А.А. Захарченко, М.А. Хажмурадов

Рассчитаны радиационно-защитные характеристики полистирол-стальных композиционных материалов. Дано сравнение эффективности ослабления потока гамма-квантов в случаях сплошного защитного слоя и защитного слоя, изготовленного в виде шариков диаметром 2 мм. Рассчитано изменение относительного ослабления поглощённой дозы композитами толщиной 10 и 50 мм. Исследована зависимость между защитными свойствами композита и его компонентным составом. Выполнена доработка технологического процесса изготовления композиционных материалов. Найдены скорости вращения системы размешивания. Установлено, что время нагрева полистирол-стальной смеси больше, чем время нагрева полистирол-вольфрамовой. При помощи методов ИК-радиометрии контролировали степень нагрева смеси и однородность теплового поля по её поверхности.

ЗАСТОСУВАННЯ МЕТОДІВ МАТЕМАТИЧНОГО МОДЕЛЮВАННЯ ДЛЯ ЗНАХОДЖЕННЯ РАДІАЦІЙНО-ЗАХИСНИХ ХАРАКТЕРИСТИК ПОЛІСТИРОЛ-МЕТАЛЕВИХ КОМПОЗИЦІЙНИХ МАТЕРІАЛІВ

В.Ф. Клепіков, Є.М. Прохоренко, В.В. Литвиненко, О.О. Захарченко, М.А. Хажмурадов

Розраховані радіаційно-захисні характеристики полістирол-стальних композиційних матеріалів. Надано порівняння ефективності послаблення потоку гамма-квантів у випадках суцільного захисного шару і захисного шару, виготовленого у вигляді кульок діаметром 2 мм. Розрахована зміна відносного послаблення поглиненої дози композитами завтовшки 10 і 50 мм. Досліджена залежність між захисними властивостями композиту і його компонентним складом. Виконано доопрацювання технологічного процесу виготовлення композиційних матеріалів. Знайдені швидкості обертання системи розмішування. Встановлено, що час нагріву полістирол-сталевої суміші більший, ніж час нагріву полістирол-вольфрамової суміші. За допомогою методів ІЧ-радіометрії контролювали ступінь нагріву суміші і однорідність теплового поля по її поверхні.