

COMPARISON OF PRODUCT IRRADIATION TECHNOLOGY ON INDUSTRIAL X-RAY RADIATION FACILITY

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The comparison of various technologies of product irradiation with X-rays (bremsstrahlung) that is generated by industrial high-power electron beam accelerators is presented in the report. Computer modeling method was used for calculation the 3 dimensional absorbed dose distributions in the product containers on moving conveyor irradiated with scanned X-ray beams. The comparison of dose uniformity ratio in the irradiated product was performed for various technologies of product irradiation with X-ray. The variants of product containers movement in front of X-ray converter in the range from 2 to 8 passes at different levels were considered.

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INTRODUCTION

Today, the intensive increase of integration the radiation technologies in various industry branches worldwide is observed. Sterilization of medical devices and pharmaceuticals, polymer cross-linking of tubes, cables, packaging materials, tire component curing, irradiation of selected food items (spices, seafood) are established technologies. An implementation of radiation technologies in various fields of industry is accompanied by magnification of amount of industrial radiation facilities, expansion of assortment of products treated by ionizing radiation, and development of new methods of product irradiation.

Main types of radiation sources of ionizing energy for industrial radiation processing are accelerated electrons, X-rays (bremsstrahlung) emitted when high-energy electrons are stopped by a heavy metal targets and gamma rays from radioactive nuclide Cobalt-60. The preferred type of radiation source is usually determined by practical process requirements, such as the minimum and maximum absorbed doses (D_{\min} , D_{\max}), dose uniformity ($DUR = D_{\max}/D_{\min}$) and dose rate, material thickness, density and shape, production rates, capital and operating costs, and ease of use. The use of electron accelerators for generation of X-ray beams represents major commercial interest in the field of radiation technologies.

High-energy ~ 10 MeV, high-power electron beams (EB) can process thin materials at high speeds, but their penetration is limited to a 10 cm in a product with density about 1 g/cm^3 . Gamma rays emitted by cobalt-60 sources are mainly used to irradiate larger packages of medical devices and foods at slower processing rates. High-energy X-rays generated by electrons with kinetic energies greater than 3.0 MeV are more penetrating than such gamma rays. In contrast to gamma rays, which are emitted in all directions from a cobalt-60 source, high-energy X-rays are concentrated in the direction of the incident electron beam, and their angular dispersion decreases as the electron energy increases. Recent increases in the available X-ray power and in the price of Co-60 sources have made X-rays a viable alternative to gamma-rays for radiation processing [1,2].

Success of application of X-ray beams in radiation processing depends largely on development of theoretical notions, semi-empirical models and computer codes for simulation of irradiation processes based on X-ray

radiation facility [3, 4]. The results of the computer simulation using Monte Carlo (MC) method of the absorbed dose mapping in the products irradiated with X-ray are discussed in the report.

1. GEOMETRICAL MODELS OF X-RAY FACILITY

Today there are industrial radiation facilities with high-power X-ray capability in Europe, Japan and North America. In all these facilities the method of product irradiation is based on principle that size of X-ray converter in scan direction overlap the size of irradiated packing box with product [1,2].

State-of-the-art pallet-X-ray facility for sterilization of medical devices based on the Rhodotron, IBA's high-power, high-energy accelerator was built by LEONI Studer Hard AG, Switzerland [2, 5]. In this facility the method of product irradiation is based on principle that size of irradiated packing boxes with product in scan direction overlaps the size of X-ray converter.

Schematic representation of the EB facilities with X-ray converter, cooling system, moving conveyor and the packing box with product related to 3 methods of product irradiation with X-ray are shown in Figs. 1,a,b and c. X-ray radiation facility with product is oriented horizontally. X-ray converter consists of a tungsten front plate, a cooling channel with water and a stainless steel back plate. Boxes with product were placed on the wooden pallets and on the conveyor platforms.

In the method 1 the size of X-ray converter in scan direction overlaps the size of packing box with product, see Fig.1,a. In this method the product was irradiated with X-ray from two opposite sides by two passes in front of X-ray converter to obtain the acceptable value of X-ray absorbed dose uniformity in the product.

In the method 2 the size of two packing boxes with product overlaps the size of X-ray converter, see Fig.1,b. It is reached due to disposition of two packing boxes with product and with two pallets vertically under each other in EB scan direction. The pallets with product are located on two horizontal conveyor lines. Two packing boxes 1 and 2 with product and with pallets will be designated as the stack of two pallets – bottom pallet (Pallet 1) and top pallet (Pallet 2). In this method the stack was irradiated with X-ray from two opposite sides by four passes in front of X-ray converter.

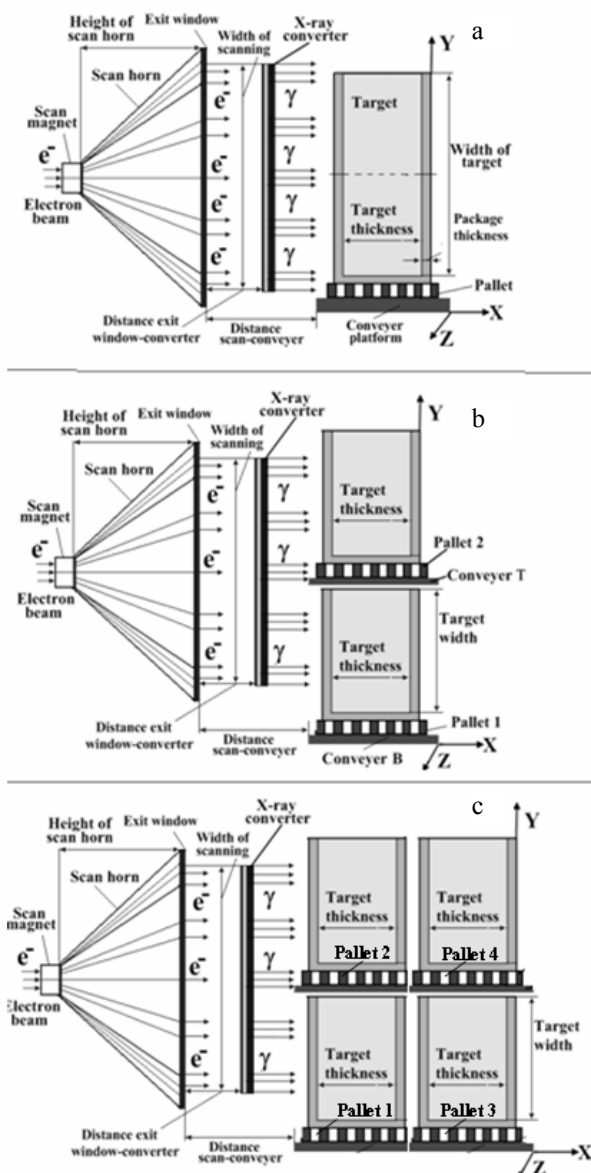


Fig.1. Geometrical arrangement of X-ray radiation facility based on the horizontally oriented EB accelerator with X-ray converter, cooling system, moving conveyor with product located on pallets. Non-divergent scanned EB.

a – Size of X-ray converter in scan direction overlaps the packing box with product.

b – Size of two packing boxes with product overlaps the size of X-ray converter. The pallet 1 with product located on the bottom conveyor, the pallet 2 with product located on the top conveyor.

c – Stack 1 comprise pallet with product 1 and pallet with product 2, stack 2 – pallet with product 3 and pallet with product 4

Stack of two pallets is rotated on their vertical axis between each pass. The top and bottom pallets of a stack are swapped after two passes. A full dose delivered to the product is divided on some “dose increment”. A “dose increment” is accomplished by 4 passes of the pallet through the X-ray field: front-top, back-top, front-bottom, back-bottom.

Geometrical model of the irradiated product in the method 3 is modification of the model in method 2, see Fig.1,c. Two stacks with two pallets and product are

irradiated simultaneously with X-ray. Stack 1 comprise pallet with product 1 and pallet with product 2, stack 2 – pallet with product 3 and pallet with product 4.

The irradiation sequence of 4 pallets with product is as follows: 1. Stack 1 with pallets 1, 2 and Stack 2 with pallets 3, 4 are rotated on their vertical axis between each pass in front of X-ray converter. 2. The top and bottom pallets of stacks are swapped after two passes. 3. The stack 1 and stack 2 are swapped after four passes. 4. The operations in points 1 and 2 are repeated.

As a result the product in each pallet was irradiated with X-ray from two opposite sides by eight passes in front of X-ray converter.

Such multipass method of product irradiation is often use in an industrial cobalt-60 gamma ray facility [7].

2. SIMULATION OF COMPLICATED METHODS OF PRODUCT IRRADIATION WITH X-RAY

In practice on radiation facility with big power irradiators the multipass, multilevel and multisided methods irradiation of product are used for improvement of quality and dose uniformity in product irradiated with EB, X-ray and gamma ray. The comparative analysis of the absorbed dose mapping in the products irradiated with X-ray was performed using the programs ModeStXR and RT-Builder developed by authors. The software ModeStXR was designed on the base of the RT-Office modules specially for MC simulation of industrial radiation processes and calculation of the absorbed dose distribution within products irradiated with stationary or scanned X-ray beams on radiation facility that is based on the pulsed or continuous type of electron accelerators in the energy range from 0.1 to 50 MeV [5]. Irradiated product is represented in form of stack of plates located in containers. Simulation of X-ray dose mapping in multi-layer targets was performed with MC method in a 3-dimensional (3D) geometrical model.

A source of electron beam, a scanner, the X-ray converter with cooling system, a conveyor line, an irradiated product and a package are considered in uniform self-consistent geometrical and physical models. The features of realization of a physical and mathematical models for X-ray processing in the software ModeStXR are as follows:

- The use of a forced method for process of producing X-ray on each step of design of electron track in a construction of the X-ray converter.

- The automatic choice of self-consistent parameters is used for simulation of an electron-photon shower. The choice is based on determination a minimum machine time for obtaining given accuracy. These parameters are the following: cutoff energy for modeling of an electron track, threshold energy of catastrophic electron-electron collisions, cutoff energy for modeling of a photon track, threshold angle of grouping electron collisions for modeling of scattering.

- The use of both a simple estimation (collision method) and the special estimation (method of crossing area) for the dose calculation.

These features allow to reduce the running time of MC simulation for receiving of the end results in about hundreds time. At simulation the X-ray dose mapping

the program ModeStXR takes into account in detail a construction of the radiation facility and requirements to regimes of irradiation in each specific radiation-technological process.

The software ModeStXR calculates the dose values into one pass X-ray irradiated product. In the complicated variant of products irradiation which is realized in the X-ray processing, the special program RT-Builder summarizes the absorbed doses distributions calculated with software ModeStXR in the 3D product for one/two/four pass/side/level irradiations.

3. RESULTS AND DISCUSSIONS

The computer simulation using Monte Carlo (MC) method of the dose mapping into irradiated product with X-ray for two methods of product irradiation was performed. High-energy X-rays are ideal for sterilizing large packages and pallet loads of medical devices. The product density range (0.1...0.5) g/cm³ is typical for the irradiation process of medical devices sterilization. The product was located in a typical European pallet of 100×120×180 cm with 15 cm wood frame.

X-ray beam was generated by scanned electron beam with electron energy 7 MeV in the tungsten converter. Optimal converter construction includes the tungsten target plate with thickness 1.1 mm, the cooling water channel – 1.3 mm, and the stainless steel backing plate – 1.0 mm. The efficiency for converting EB power to X-ray power in the forward direction is approximately 12.9%. This relatively low efficiency can be compensated by using high-power EBs to produce X-ray dose rates sufficient for industrial radiation processing.

Irradiation regimes of the polyethylene target with density in the range (0.1...0.5) g/cm³ were as follows: EB energy – 7 MeV; EB current – 100 mA; target thickness – 100 cm (axis X); target width in direction of X-ray scanning – 180 cm (axis Y); target length in direction of conveyer travel – 120 cm (axis Z); X-ray scan width (W_{scan}) – in the range (160...230) cm; non-diverging X-ray scanning regime; size of wooden pallets in scan direction – 15 cm; conveyer speed – 1 cm/s.

Figs.2,a,b represent the absorbed dose profiles in the pallet with polyethylene product irradiated with scanned X-ray beam by 2 passes from opposite sides through the X-ray field. (See Fig.1,a) Product size is 100 cm (axis X), 180 cm (axis Y), 120 cm (axis Z). Product density is 0.15 g/cm³. In all volume of irradiated product the dose uniformity ratio is about DUR=1.7.

Figs.3,a,b represent the absorbed dose profiles in the pallet with polyethylene product of density 0.15 g/cm³ irradiated with scanned X-ray beam. The pallet irradiated by 4 passes through the X-ray field in accordance with geometrical model in Fig.1,b. Fig.3,a shows the dependence in the X-ray dose uniformity from value of X-ray scan width W_{scan} in vertical direction. For the scan width W_{scan} = 200 cm the optimal value of dose uniformity ratio $DUR = D_{max}/D_{min}$ is 1.06. The same tendency is observed for the dose profile in the center of incident surface (Y, Z) along scan direction. For horizontal X-ray absorbed dose profiles in the cross section (X,Y) in the product center Z=60 cm the dose uniformity DUR is 1.18, see Fig.3,b.

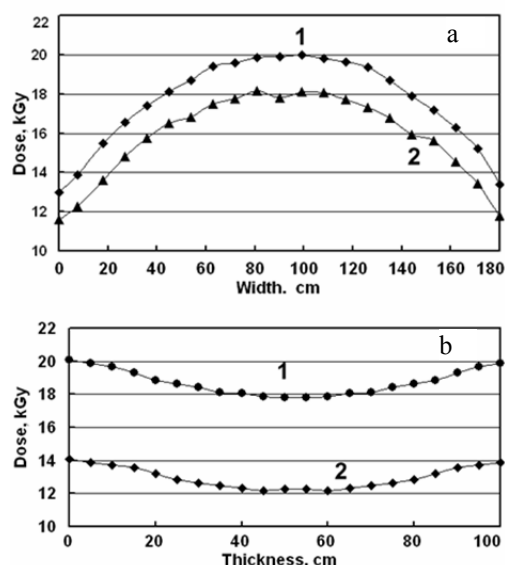


Fig.2. Vertical and horizontal X-ray absorbed dose profiles in the pallet with polyethylene product, irradiation by 2 passes through the X-ray field.

a – Vertical X-ray absorbed dose profiles in the product in scan direction: Curve 1 – product center (X=50 cm). Curve 2 – product surface (X=0 cm). b – Horizontal

X-ray absorbed dose profiles in the cross section (X, Y), Z=60 cm. Curve 1, Y=90 cm. Curve 2, Y=0 cm. Scan width W_{scan} = 184 cm

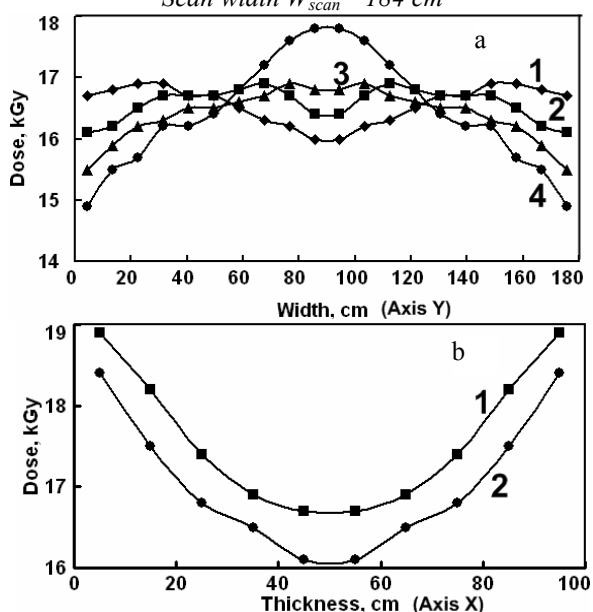


Fig.3. Vertical and horizontal X-ray absorbed dose profiles in the pallet with polyethylene product, irradiation by 4 passes through the X-ray field. a – X-ray vertical absorbed dose profiles in the center (X=50 cm) of polyethylene product for various values of scanning width W_{scan} in the range of (160...230) cm.

1 – W_{scan} = 190 cm. 2 – W_{scan} = 200 cm.

3 – W_{scan} = 210 cm. 4 – W_{scan} = 230 cm; b – X-ray horizontal absorbed dose profiles in the cross section (X, Y), Z=60 cm. Curve 1, Y=90 cm. Curve 2, Y=0 cm.

Scan width W_{scan} = 200 cm

In all volume of irradiated product at scan width W_{scan} = 200 cm the dose uniformity did not exceed the value DUR=1.2. That is less in comparison with 2 passes irradiated product, where DUR=1.7.

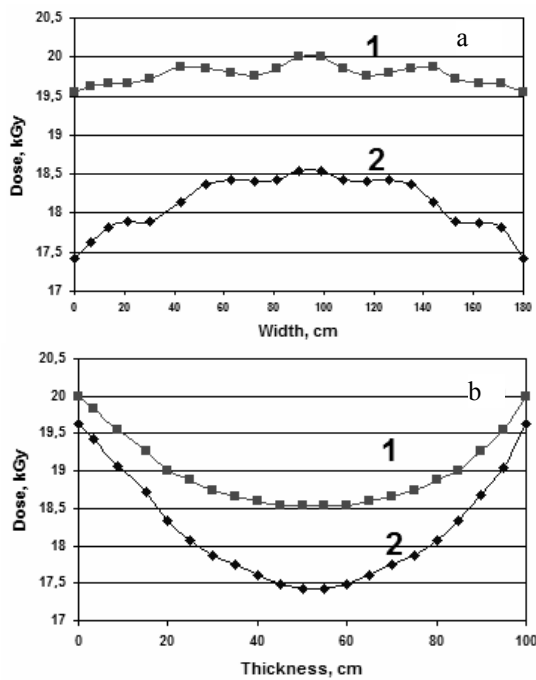


Fig.4. Vertical and horizontal X-ray absorbed dose profiles in the pallet with polyethylene product of density 0.15 g/cm^3 , irradiation by 8 passes through the X-ray field. a – Vertical X-ray absorbed dose profiles in the product in scan direction: Curve 1 – product center ($X=50 \text{ cm}$). Curve 2 – product surface ($X=0 \text{ cm}$). b – Horizontal X-ray absorbed dose profiles in the cross section ($X, Y, Z=60 \text{ cm}$). Curve 1, $Y=90 \text{ cm}$. Curve 2, $Y=0 \text{ cm}$

Figs.4,a,b represent the absorbed dose profiles in the pallet with polyethylene product of density 0.15 g/cm^3 irradiated with scanned X-ray beam. The pallet irradiated by 8 passes through the X-ray field in accordance with geometrical model in Fig.1,c. Figs.4,a,b have shown that vertical and horizontal X-ray absorbed dose profiles are similar to dose profiles on the Figs.3,a,b. In all volume of irradiated product the dose uniformity did not exceed the value $\text{DUR}=1.15$. This value is nearly the same as for case of four pass irradiated product.

Dependence of dose uniformity ratio in the product irradiated with X-ray as function of the product density in the range of $(0.1 \dots 0.4) \text{ g/cm}^3$ is shown in Fig.5. Curve 1 relates to product irradiated by 2 passes, Curve 2-4 passes, Curve 3-8 passes through the X-ray field from opposite sides.

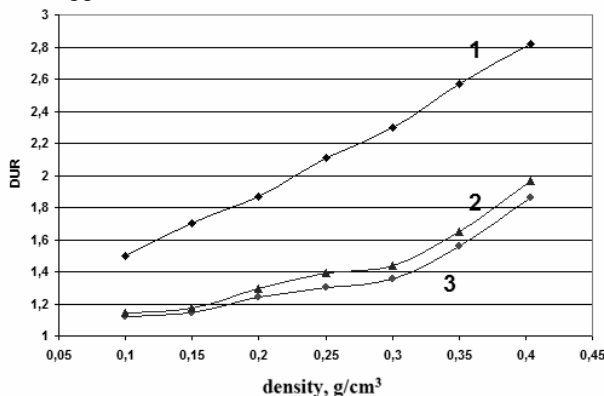


Fig.5. Dependence DUR as function of product density

Fig.5 shows the strong dependence of the DUR values as function of product density in the range of $(0.1 \dots 0.4) \text{ g/cm}^3$. As it is seen from Figs.2,3,4 and 5, the value of DUR is greater in product irradiated with scanned X-ray by two passes from opposite sides in comparison with method of product irradiation by 4 and 8 passes through the X-ray field. It limits of practical use the method of product irradiation with scanned X-ray beam by two passes only in products with small densities where $\text{DUR} < 2$.

The computer simulation of the dose mapping into X-ray irradiated product which consists of two pallets containing different products with different densities 0.1 and 0.3 g/cm^3 was performed for two cases: 1) two pallets were located on two horizontal layers under each other; 2) two pallets were located on one horizontal layer with 10 cm lateral air gap between products. Analysis of simulation results have shown that methods of product irradiation by 4 and 8 passes allow to irradiate simultaneously the pallets containing various products with different densities and the value of DUR does not change more than 5% , which is acceptable for the X-ray processing.

CONCLUSIONS

The MC computer simulations of the absorbed dose mapping in the products irradiated with X-ray of various methods such as 2, 4 and 8 product passes in front of X-ray irradiator were performed. The following features in the X-ray the absorbed dose mapping were observed:

- the dependence in the X-ray dose uniformity from value of X-ray scan width W_{scan} in the vertical direction;
- the minimum value of dose uniformity ratio for optimal value of X-ray scan width W_{scan} ;
- the strong dependence of the DUR values as function of product density in the range of $(0.1 \dots 0.4) \text{ g/cm}^3$;
- the value of DUR is greater in product irradiated with scanned X-ray by two passes from opposite sides in comparison with methods of product irradiation by 4 and 8 passes through the X-ray field;
- the methods of product irradiation by 4 and 8 passes allow to irradiate simultaneously the pallets containing different products with different densities and the value of DUR does not change more than 5% , which is acceptable for the X-ray processing.

The program ModeStXR can be used as predictive tool:

- for optimization X-ray irradiator construction on stage of design the X-ray radiation facility;
- for X-ray dose mapping and various methods of product irradiation;
- on stage of commissioning of new X-ray radiation facility based on EB accelerator;
- on stage of optimization of radiation facility parameters and regimes irradiation in the specific X-ray processing;
- at interpretation of predictions for processing results of dosimetric data;
- at performance of actions and procedures prescribed with X-ray dosimetric standards and the standards for process of radiation sterilization;
- for advanced training and educating of the qualified specialists and students in the fields of the transport

of ionizing radiation through heterogeneous objects, in the industrial EB, X-ray radiation technologies and in the computational EB and X-ray dosimetry.

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СРАВНЕНИЕ ТЕХНОЛОГИИ ОБЛУЧЕНИЯ ПРОДУКЦИИ В ПРОМЫШЛЕННЫХ УСТАНОВКАХ ТОРМОЗНОГО ИЗЛУЧЕНИЯ

В.Т. Лазурик, В.М. Лазурик, Г.Ф. Попов, Ю.В. Рогов, Г.Э. Саруханян

Приводится сравнение различных технологий облучения продукции тормозным излучением (ТИ), которое генерируется на промышленных ускорителях электронов большой мощности. Методом компьютерного моделирования рассчитывается 3-х мерное распределение поглощенной дозы в продукции, расположенной в контейнерах на движущемся конвейере, и облучаемой сканирующими пучками ТИ. Для различных технологий облучения продукции ТИ проведено сравнение неоднородности поглощенной дозы в облучаемой продукции. Рассматривались варианты перемещения продукции в контейнерах параллельно плоскости конвертера ТИ от двух до восьми проходов на разных уровнях.

ПОРІВНЯННЯ ТЕХНОЛОГІЙ ОПРОМІНЕННЯ ПРОДУКЦІЇ В ПРОМИСЛОВИХ УСТАНОВКАХ ГАЛЬМІВНОГО ВИПРОМІНЮВАННЯ

В.Т. Лазурик, В.М. Лазурик, Г.Ф. Попов, Ю.В. Рогов, Г.Е. Саруханян

Наводиться порівняння різних технологій опромінення продукції гальмівним випромінюванням (ГВ), яке генерується на промислових прискорювачах електронів великої потужності. Методом комп'ютерного моделювання розраховується 3-вимірний розподіл поглиненої дози в продукції, розташованій в контейнерах на конвеєрі, що рухається, і опромінюваної скануючими пучками ГВ. Для різних технологій опромінення продукції ГВ проведено порівняння неоднорідності поглиненої дози в опромінюваній продукції. Розглядалися варіанти переміщення продукції в контейнерах паралельно площини конвертера ГВ від двох до восьми проходів на різних рівнях.