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2.4 Electron beam Processing System

Masayuki KASHIWAGI
Nissin-High Voltage Co. Ltd., Kyoto, Japan

1. Introduction

Electron beam Processing Systems (EPS) are used as useful and powerful tools in many industrial application fields such as the production of cross-linked wire, rubber tire, heat shrinkable film and tubing, curing, degradation of polymers, sterilization and environmental application. In this paper, the feature and application fields, the selection of machine ratings and safety measures of EPS will be described.

2. Feature of EPS

2.1 What is Electron Beam?

Electron beam (EB) means the flow of electrons with energy which is taken to the electrons from filament (cathode) as kinetic energy by moving in high electric field (Acceleration). It is similar that a stone dropped down from high roof gets the energy by gravitation of earth. EB makes chemical reaction in the irradiated material. The accelerated electrons are decelerated because of its minus charge and give a part of its energy to the atom, which generates secondary electron as a result of reaction with the atom. The secondary electrons interact with another atom, generate many secondary electrons like a shower and lose their energy in the irradiated material. The lost (or absorbed) energy generates active free radicals, which make chemical reaction in the irradiated material. Because electron is one of components in atom, electron beam is carrier of energy purely.

2.2 Feature of EPS

EPS has the following feature.

a) EB gives its energy directly to the irradiated material;

Therefore, the energy utilization efficiency is extremely high. In a case of normal thermal chemical reaction, the energy is given to activate the molecular and to make chemical reaction between each molecular as the result. Therefore normal thermal chemical reaction can be said indirect injection of energy.

In EB irradiation, the unit of kilo-gray (kGy) is used generally as energy absorbed in the material (dose) and the energy of 10 kGy is only 2.4 cal. for 1 g of water. Usually, dose for radiation chemical reaction is several ten kGy up to 200 kGy, so the material, which is weak for high temperature such as plastics can be treated. Also the EB chemical reaction can occur in wide range of low and high temperature, so the reaction is not affected for secondary or third reaction.

b) It is not necessary to mix third material such as catalyst for chemical reaction.

c) EPS has very large capacity for irradiation process.

EB is particle beam and has higher energy transmission rate compared with electromagnetic waves such as electric wave, visible ray, UV, X-ray and gamma ray. Now, EPS with the capacity of 100 kW above is manufactured and mass irradiation processing is available.

d) Easy operation

Because EPS is an electric machine, the start and stop of production or reaction can be made only switch on or off.

e) Easy maintenance

Because EPS is not radioisotope such as Cobalt-60, the maintenance work is excellent easy and safety because it can be made on the condition of switch off.

3. Electron beam Processing System (EPS)

3.1 Type and feature of EPS

EPS is simply said as the processing system using electron accelerator which generates thermal electrons from cathode, accelerates the generated electrons, gets them into air through thin metal foil, irradiates material and makes chemical reaction in the irradiated material. EPS is classified in various kinds and has each feature.

3.1.1 Type of Acceleration

There is a classification by acceleration method of electron. One is the method using DC high voltage and the other is the method using high frequency voltage.

The acceleration method using DC high voltage is that the DC high voltage as high as acceleration energy is generated and the thermal electrons from filament as a cathode are accelerated in the electric field of this DC high voltage. In this method, the continuous beam is available and the energy conversion efficiency, which is the ratio of output and input capacity (DC/AC) is quite high. But it is necessary to generate as same DC high voltage as acceleration energy and this makes the size of DC power supply bigger according with the acceleration energy. The limitation of practical utilized energy range is said 5 MV.

The acceleration method using AC high frequency is that the thermal electrons are repeatedly accelerated in the electric field of high frequency voltage such as linear accelerator, betatron and synchrotron. And also there is a single cavity type using repeated acceleration system (Rhodotron from IBA). In any case, this high frequency acceleration

method can make machine size small but poor energy conversion efficiency because repeated acceleration using high frequency electric field.
In industrial application field, the DC acceleration type machine has been used generally because the good energy conversion efficiency but Linear accelerator (Linac) and Rhodotron with 10 MeV energy become to use in the sterilization field, which is needed big penetration.
3.1.2 Type of DC Power Supply

DC power supply is one of most important component in DC acceleration type. Therefore there is a classification by type of DC power supply. DC power supply is divided in three types roughly. One is Cockcroft-Walton type and another is transformer type. The other is Van-de-Graaff type, which generates the DC high voltage carrying electron charge on insulation belt has poor capacity and is used in research and development purpose only.

Cockcroft-Walton type is a circuit using capacitor in series and because the frequency of several kilo hertz (kHz) is used as input power, the energy conversion efficiency of 60 % to 80 % is relatively high. The modified circuit of Cockcroft-Walton is Shuenkel type in which the capacitors in parallel are adopted. In this circuit, the capacitor at high voltage side is charged the maximum voltage and the actual capacitor can be not adopted, therefore the stray capacitance between high voltage terminal and ground electrode is used as capacitor. As the result, it is necessary to adopt very high frequency as input power and this limits energy conversion efficiency low.

Transformer type is divided in two types. One is grounded core type which is insulated DC high voltage between primary and secondary coils and the other is insulated core type which is insulated DC high voltage divided among secondary step up coils. In both type, the rectifier circuits are provided to plural secondary coils and connected in series at DC sides to generate high voltage.

In a grounded core type, the magnetic flux connection is good, so DC power supply with large beam current capacitance up-to 1000 mA ca be manufactured now. But the maximum rated voltage is limited 1000 kV because of difficulty of insulation. The largest merit of this type DC power supply is that the magnetic flux connection is very good, the commercial frequency can be used basically, high frequency power supply as input is not used, and so the high energy conversion efficiency more than 90 % can be achieved.

In an insulated core type, cores are divided and insulated in each step up stages and are not necessary to insulate DC voltage generated in each step up stages, so the high voltage machine with 2000 kV can be manufactured. But because of rough magnetic connection between primary and secondary coils, the energy conversion efficiency is lower than it of ground core type and beam current capacity is also small.

3.1.3 Type of Scanning

EPS is also divided in scanning type and non-scanning type by the method of electron beam extraction. In a scanning type, the spot electron beam accelerated in an acceleration tube is scanned to the necessary irradiation width by electro-magnetic field. It is similar to a cathode ray tube of TV. On the other hand, in non-scanning type, electrons from big cathode (multi filaments) are generated as wide as irradiation width and accelerated in one step. It is similar to triode. In non-scanning type, because of the structure without acceleration electrodes and scanning chamber, machine can be made simple and small, but the acceleration voltage is limited up-to 300 kV. In scanning type, the acceleration voltage is divided and applied to the multi acceleration electrodes, so the high voltage machine up-to 5 MV can be made but machine size becomes big.

3.2 Constitution of EPS

For example of scanning type machine, EPS consists of a power supply, an acceleration tube assembly, a scanning chamber, window, a vacuum system and control system.

A Cockcroft-Walton type DC power supply and acceleration tube system are enclosed in a pressure vessel. The pressure vessels are filled with SF6 gas to insulate the high voltage. The D.C. power supply generates high voltage via the Cockcroft-Walton circuit, which is driven by a high frequency system. The DC high voltage is applied to the top of an acceleration tube assembly, where a filament assembly provides as a source of electrons. The filament is heated using a motor generator set. The electrons are emitted from the filament at a negative potential and are accelerated through the high vacuum acceleration tube, scanned electro-magnetically in the scanning chamber, and then passed through a thin window foil to irradiate the product.

4. Application of EPS

4.1 Application of Cross-linking

The cross-linking is one of polymerization which is purpose to improve the characteristic such as heat resistance by chemical combination between molecules and has been used for production of heat resistance electric wires, heat resistance film and sheet and heat shrinkable tube and film from early stage. In Japan, the production of heat resistance electric wires was started at first at Sumitomo Electric Industries and Hitachi Cable, etc. and then the production of heat shrinkable tube and foamed polyethylene at Toray and Sekisui was started. Foamed polyethylene was invented in Japan and is one of leading fields in the world. EPS with acceleration voltage of 500 kV up to 3 MV and beam current of 50 mA up to 100 mA are used.

The technology to use cross-linking in tire manufacturing process was started at Goodyear and Firestone in USA at first but research and development work was also made actively in Japan. Tire is manufactured by the process to stick and shape with several kind of thin rubber composed by many kind of ingredient and vulcanize it in the condition of high pressure and high temperature. In the process of shaping and vulcanizing, if the strength of raw rubber (green strength) is not enough, the defect such as discrepancy of textile code occurs. To avoid this defect, the pretreatment by irradiation of electron beam was developed. At present state, EPS of 19 sets in 5 manufacturers in Japan have been used and this is also one of leading fields in the world.

4.2 Application of Radical Polymerization

The curing of paint and coat using radical polymerization was started in 1960's and pilot plants were installed at several paint manufacturers. As production lines, painting process of automobile parts at Ford in USA and Suzuki Motors in Japan, coating of metal coil at Shin-Nippon-Steel and wood panel coating were installed. After that time, the main trend of curing technology was moved into utilization of UV but the utilization of EB was stagnated for long time. In 1980's, EB units of laboratory type were sold and introduced to paint manufacturers and research institutes of many companies. At present state, EPS are used in the production process of release paper, intaglio printing, adhesive materials and transfer film and spread its application fields. In future trend, EB, which is used for the process of deep color and shade material, will coexist with UV. EPS with acceleration voltage of 300 kV or less so-called low energy EPS is used for this field.

4.3 Application of Graft Polymerization

Graft polymerization, in which monomer is polymerized like grafting to the trunk of polymer chain, is used as one process to add the deferent characteristic of monomer to it of original polymer as one of improvement technologies of polymer. It is used for the production process of ion exchange membrane, separator of battery, water absorbent polymer and anti-fog film. EPS with acceleration voltage of 300 kV to 500 kV is applied.

4.4 Other Application

a) Environmental Preservation

Flue Gas Treatment as utilization of electron beam is typical example of application to environmental preservation. This technology was developed originally in Japan in 1970's. Coal or oil fired flue gas which includes SOx and NOx is irradiated prior and react into complex salt of (NH4)2SO4 and NH4NO3 with ammonia (NH4). The bi-product is removed easily by bag filter or electrostatic precipitator and can be used as powdered fertilizer. EPS with acceleration voltage of 700 kV to 800 kV and beam current of 400 mA to 500 mA is used for this application.

Decomposition treatment of volatile organic compound (VOC) and dioxins by EB irradiation are under study. EPS with acceleration voltage of 300 kV or below and beam current of several ten mA will be used respectively.

Wastewater and sludge treatment by EB irradiation has been studied for 30 years in many institutes and much data was accumulated. Recently, treatment of wastewater from dye factories and other industries has been reported in Korea and Brazil.

b) Application for semiconductor Device

Recently, the application for semiconductor device, in which thyristor used in inverter is irradiated by EB to make lattice defect for the improvement of switching characteristic. In this application, the point of technology is wafer handling and irradiating system but not machine ratings of EPS.

c) Application of Sterilization

Radiation sterilization for medical supplies is used by gamma ray from Co-60 generally. Even now, the share of EB treatment for this purpose is less than 10 % compared with gamma ray treatment in economical effect. EB sterilization was started in 1991 in Japan using EPS with acceleration voltage of 5 MV. Since then, EPS for sterilization increased the number of installation up to 8 sets (4-in house and 4-tole service). The feature of high energy with 5 MV to 10 MV and high power with 100 kW to 200 kW will bring application of EPS to extensive medical supplies.

In the food irradiation, potato is only one food permitted by gamma ray in Japan. This permission was made in 1974. Since then, no request for permission of food irradiation has been continued but about 220 kinds of food are permitted in 52 countries worldwide. Especially spices are permitted in 47 countries and actually irradiated by EB or gamma ray in 27 countries. In Japan, Japan spice industry requested for permission of spice irradiation to the government in 2000.

From different viewpoint, for the purpose of surface sterilization of grain, low energy electron, called as "Soft Electron" which has lower than 300 keV, is paid attention in Japan. As germ is located only surface of grain, low energy electron beam is very effective for sterilization because of its poor penetration.

5. Electron beam Processing System (EPS)

5.1 Selection of EPS ratings

The selection of EPS is decided by consideration to irradiate what material with how thick and wide, how much dose, how to handle, in what atmosphere. The parameter to decide the ratings of EPS is acceleration voltage, beam current and irradiation width. The actual selecting work will be done as follows but it is better to consult with manufacturer of EPS because of limitation of manufacturing.

What	Material to be irradiated	Material quality Material width Material thickness
How	Amount to be irradiated	Production amount
How	Dose to be irradiated	Necessary dose absorbed to make reaction
How	Material handling system	Single pass or multi passes of irradiation
How	Irradiation condition	Inert gas atmosphere Air atmosphere

5.2 Acceleration Voltage

Acceleration voltage is decided what material and how much penetration should be irradiated. Actual selection work of acceleration voltage is used penetration curve. Generally the depth of 60 % relative dose is said the effective thickness. The thickness is normalized by specific gravity of 1.0; therefore in irradiation of material with different specific gravity, the thickness should be calculated as specific gravity 1.0. When the thicker material than penetration can be treated by both side irradiation. But in a case of irradiation to high insulation material such as polyethylene, the discharge by charged up electrons inside material should be considered. (Lichtenberg discharge)

5.3 Beam Current

Beam current is expressed the number of electrons and is the parameter related to dose and handling speed. The relation formula is shown as follows.

$$D = \frac{\triangle E}{\triangle R} \cdot \frac{\eta \cdot I}{W \cdot V} \times 1000$$

Here is, D : dose (kGy)
I : beam current (mA)
W : irradiation width (cm)
V : handling speed (cm/s)
η : irradiation efficiency (normally 0.9)
$\triangle E/\triangle R$: energy absorption ratio ($MeV/g/cm^2$)

The energy absorption ratio($\triangle E/\triangle R$) is decided by acceleration voltage, widow foil thickness, distance between window foil and irradiated material. Beam current is limited by irradiation width because of cooling efficiency of window foil for energy loss of electron beam.

6. Safety Measures

In design, construction and operation of an EPS, it is necessary to consider sufficient safety measures such as x-ray shielding, ozone control and interlock system described below.

6.1 X-ray Shielding

X-rays are generated in the irradiation area by the interaction of fast electrons and materials such as the window foil, the water-cooled beam catcher and/or the customer's product. X-ray shielding for the EPS must be provided to reduce the radiation to acceptable levels.

. The radiation enclosure or shielding can be constructed using a number of materials such as concrete, lead, steel and sometimes in combinations to reduce the X-ray output to acceptable levels. The safety standard for x-ray should be prescribed by the government rule or authority recommendation such as the ICRP (International Committee of Radiation Protection). Typical levels outside the enclosure or shielding area are 1 mSv/2000 hr. (0.5 mSv/hr) for uncontrolled areas

In general, there are 2 (two) main areas to be considered, these are classified below:

a) The Irradiation Area

This is a highly controlled area. NO PERSONNEL are permitted in this area when the high voltage power supply of EPS is energized. All maintenance operations are only permitted with the approval and supervision of the plant safety office.

b) Areas Outside the Irradiation Area

All areas except a) are classified as uncontrolled areas.

6.2 Ozone Control

When electron beam passes through air, a large amount of ozone is generated, which causes violent irritation in case of higher ozone concentration than 1 ppm. The presence of ozone is perceptible of its pungent odor. An experienced person can sense its presence even if low concentration of 0.01 ppm.

The regulatory maximum permissible concentration of ozone for daily exposure of 8 hours/day was set to 0.1 ppm in 1954 in USA. In Japan, the working group for air pollution of the central council on anti-pollution measures recommend in 1972 in its "technical committee report on environmental criteria for nitrogen oxides, etc." that the hourly mean concentration of photo chemical oxidant, most of part of which is ozone, is 0.06 ppm or less. Therefore, suitable measures to avoid ozone hazard must be considered according to the local regulations.

6.2.1 Ozone Generation

The amount of ozone generated is determined by the energy loss of electron beam in its air path and beam current. The ozone generation rate is given 0.11 kg/kWh and calculated in the following form.

$$Q = 0.11\ W$$

Here is W: energy loss in a unit time in air (kW)

Q: amount of ozone generated (kg/h)

6.2.2 Disposal of exhausted ozone

The generated ozone must be exhausted and disposed by suitable method such as followings.

a) Combustion method

Ozone can be decomposed at temperature of 450 degrees centigrade.

b) Catalyst treatment method

Ozone can be decomposed by Manganese dioxide.

c) Activated charcoal method

Ozone can he decomposed by activated charcoal, which is made as the mixture of charcoal and silica alumina gel.

d) Diffusion method

Ozone is exhausted and diffused in the air from a high chimney.

In these cases, activated charcoal method and diffusion method are ordinarily selected.

6.3 Interlock System

. It is also necessary to consider an interlock system and a safety key system. These are typical requirements for entrance/exit doors, all of which are usually under a set of government regulations.

The basic interlock system is designed to prevent unauthorized personnel from entering to the radiation area while the EPS is in operation. The system is designed to shut down the EPS if the entrance door or other interlocks are activated.

6.3.1 One Key System

The one key system is highly recommended for all EPS equipment. Only one key is used at the following locations:

a) EPS operational terminal

b) Main shield door key lock

c) Selector switch in the shield room

The EPS is designed to operate when the one key is inserted into the operation terminal and turned to the ON position. To open the shielding door the single key must be removed from the operation terminal, this will shut down the EPS, similar to an emergency stop.

6.3.2 Door Interlocks

Redundant door interlocks should be provided to ensure that the system will shutdown should personnel try to enter the shield room when the system is in operation. Two or more separate limit switches connected in series are recommended to provide on the door. These switches will be a part of the EPS operational sequence conditions. When either one or all of these switches are activated, the EPS cannot be operated. An indication will be lit on the operation terminal of the EPS so the operator can determine the cause of the interlock. If one of the door interlock switches is activated during EPS operation, the system is designed to shut off.

7. Cost Estimation

The cost estimation to install EPS is very difficult to do generally because the cost such as labor charge, construction and material handling system is different in each country. The following items should be considered for cost estimation.

a) Electron accelerator

b) X-ray shielding

c) Material handling system

d) Other auxiliary equipment such as blower, ozone treatment, SF6 gas and SF6 gas handling equipment

e) Installation work including wiring piping

f) Transportation

g) Other items such as running cost, labors charge, depreciation and interest