HIGH POWER ELECTRON ACCELERATORS FOR FLUE GAS TREATMENT

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Abstract

Flue gas treatment process based on electron beam application for SO_2 and NO_x removal was successfully demonstrated in number of laboratories, pilot plants and industrial demonstration facilities. The industrial scale application of an electron beam process for flue gas treatment requires accelerators modules with a beam power 100-500 kW and electron energy range 0.8-1.5 MeV. The most important accelerator parameters for successful flue gas radiation technology implementation are related to accelerator reliability/availability, electrical efficiency and accelerator price. Experience gained in high power accelerators exploitation in flue gas treatment industrial demonstration facility was described and high power accelerator constructions have been reviewed.

1. INTRODUCTION

Above 1200 accelerators have been build for radiation processing (the total number of accelerators applied in science, medicine and industry amounts above 15 000). The recent progress in accelerator technology development based on new accelerator constructions and modern components application is focused on:

- Accelerator technology perfection (electrical efficiency, cost);
- Reliability according to industrial standards;
- Accelerators for MW power beam level;
- Compact accelerator constructions;
- Very low energy, powerful accelerators.

Although there are many different types of accelerators offering a wide range of performance ratings, only few would be suitable for particular application. The basic specifications for the electron energy, beam current and beam power should be derived from the process requirements (absorbed dose distribution, the product size, the shape and density, and the throughput rate) to ensure satisfactory results with minimum capital and operating costs [1]. The full scale industrial implementation of an electron beam process for flue gas treatment requires accelerators modules with a beam power 100-500 kW and electron energy range 0.8-1.5 MeV. Power plant offering 500 MW of electrical power may require above 5 MW of electron beam power deposited the flue gas emitted during combustion process [2].

2. ACCELERATOR TECHNOLOGY FOR ENVIRONMENTAL APPLICATION

Accelerator technology was found to be useful in many radiation processes applied for environment protection. Table I illustrates capability to electron beam treatment in gas, liquid and solid phase of matter.

TABLE I. RADIATION TECHNOLOGY APPLIED IN ENVIRONMENT PROTECTION

Phase	Object	Additives	Process
Gas	Flue gas	SO_2; NO_x	Removal
	VOC	Organic compounds	Degradation, removal
Liquid	Drinking water	Chemical pollutants	Degradation, removal
	Wastewater	Bacteria; viruses; parasites	Hygenizataion
	Industrial wastes	Organic and nonorganic compounds	Degradation, removal
Solid	Sewage sludge	Bacteria; viruses; parasites	Hygenizataion
	Solid materials	Agriculture wastes	Transformation

The selection of accelerator parameters depends on technological process requirements which are directly connected to density of irradiated material. Flue gas treatment process has been investigated since 1970, when first experiment in that field was performed in Japan [3]. The research study was carried on in many laboratories in different countries as it can be seen in Table II. According to presented data accelerator performances in laboratory facilities for flue gas treatment are not critical. Energy range covers 0.22-12 MeV and beam power 3.6-22 kW. Efficient utilization of electron beam and related to that economical parameters of laboratory facilities with flue gas flow rate bellow 1000 Nm^3/h are not important from point of view technology development.

TABLE II. BASIC PARAMETERS OF ACCELERATORS APPLIEDIN FACILITIES FOR FLUE GAS TREATMENT

Type of installation	Energy [MeV]	Power [kW]	Type of accelerator	Company, country
Laboratory installation	12	1.2	Linac	Ebara, Japan
	3	15	Cockroft-Walton	JAERI, Japan
	1.2	1.2	Dynamitron	University, Tokyo, Japan
Flue gas flow rate:	0.22	22	Transformer	Uni. Karlsruhe, Germany
<1000 Nm^3/h	0.3	3.6	„	KfK, Germany
	0.7	5	„	INCT, Poland
Pilot installation	0.75	2x 45	-	Ebara, Japan
	0.8	2x 40	-	Research Cottrel, USA
Flue gas flow rate:	0.8	2x 80	-	Ebara, Japonia
1000-20000 Nm^3/h	0.3	2x 90	Curtain	Badenwerk, Germany
	0.5	15	Cockroft-Walton	KfK, Germany
	0.5	15	„	Ebara, Japan
	0.7	2x 50	Transformer.	INCT, Poland
	0.8	3x 36	„	Ebara, Japan
	0.5	2x 12.5	Cockroft-Walton	Ebara, Japan

The accelerator parameters for pilot plant facilities with flow rate 1000-20000 Nm^3/h are more specific. Electron energy is within the range 0.3-0.8 MeV and beam power which depends on flue gas flow rate is 25-180 kW (Table II). The principal accelerator parameters of accelerator module according to present experience for pilot and industrial facility for flue gas treatment according to described above accelerator selection definition should be as follow:

- Electron energy 0.8 – 1.5 MeV
- Beam power 100 – 500 kW

Experience gained in practical application of accelerator technology for environmental application shows clearly that the accelerator selection criteria should be extended and seriously considered regarding the following accelerator performances:

- Accelerator reliability/availability,
- Accelerator electrical efficiency,
- Accelerator price.

2.1. Accelerator reliability/availability

Accelerators applied for flue gas treatment facilities were in primary approach installed in power stations where electricity production is based on fossil fuel combustion process. The power station availability coefficient is very high and typical operation period is within the range 6000 - 8000 h/year. The same time accelerator availability coefficient should be above 95% level to fulfill requirements according to power industry standards.

The exploitation of electron accelerators installed in Pomorzany Power Station, Szczecin, Poland reviled the number of long lasting failures which were related to: broken isolation of HV transformers, output windows implosions, accelerating sections deformation, HV cable connector breakdown, and output window water cooling system improper design. The characteristic features of exploitation of prototype transformer accelerators installed in Pomorzany Power Station provided by NHV from Japan were connected to limited exploitation experience, parameters on the edge of present limits, improper design of selected systems, difficulties in spare parts availability, difficult interchangeability of the components, no share reliability experience policy, and no active efforts to redesign faulty systems according to exploitation experience.

Some of listed above technical shortages can be overcome by practical implementation the experience gained in accelerator technology development by different accelerator manufactures. High power accelerator reliability/availability must be dramatically improved to meet industrial standards. Support of accelerator technology dedicated for environment protection should be provided by governmental and international institutions to overcome accelerator reliability/availability problem and high risk and low direct profit in this particular application.

2.2. Accelerator electrical efficiency

Accelerator electrical efficiency depends on principle of accelerator operation and auxiliary equipment provided by certain accelerator manufacturer. Electrical energy consumption which is defined by beam power and electrical efficiency has significant influence on cost of accelerator exploitation. Table III illustrates the share of electrical energy cost in exploitation costs of radiation sterilization facility and facility for flue gas treatment where accelerators with different electrical efficiency were applied. As it can be noticed easily the share of electrical energy cost in exploitation costs depend primary on the investment cost related to beam power level. High investment cost of radiation sterilization facility means low share of electrical energy cost in spite of very low electrical efficiency of linear accelerators which are commonly used in such facilities. If such investment cost is low, like for flue gas treatment facility, the share of bank credit repayment in exploitation cost is also low. That is why the share of electricity cost in flue gas treatment facility is high in spite of relatively high electrical efficiency of applied accelerator.

TABLE III. THE COMPARISON OF SELECTED EXPLOITATION COEFFICIENT OF FACILITIES FOR RADIATION STERILIZATION AND FLUE GAS TREATMENT

Type of cost [k$]	Radiation sterilization; Accelerator parameters 10 MeV, 20 kW;	Flue gas treatment; Accelerator parameters 0.8 MeV, 1200 kW;
Facility investment cost	7500	18000
Facility investment cost per 1 kW beam power [$]	375	15
Type of accelerator	Microwave linac	Transformer
Electrical efficiency	10%	80%
Exploitation cost: - total - electrical energy	 1550 40	 2960 480
Share of electrical energy cost in exploitation costs	2.6%	16.3%

TABLE IV. ELECTRICAL SUPPLY OF ELECTRON ACCELERATOR EPS 800-375, NISSIN HV

Beam power	600 kW
Power consumption	
Power supply 6 kV, x 3 Control power 380 V, x 3 Vacuum power 380 V, x 3	667 kW 10 kW 5 kW
Power consumption	682 kW
Power efficiency	88 %
Ventilation and air cooling	
Window cooling blower	150 kW
Ozone exhaust blower	11 kW
Total power consumption	843 kW
Total power efficiency	71 %

The role of electrical energy consumed by auxiliary equipment is well described by data provided in Table IV. The optimization of all accelerator systems to minimize electrical energy consumption should be performed by accelerator manufactures to improve electrical efficiency coefficient. The block diagram presented on Fig. 1 shows the main components of high power accelerator which may consume electrical energy.

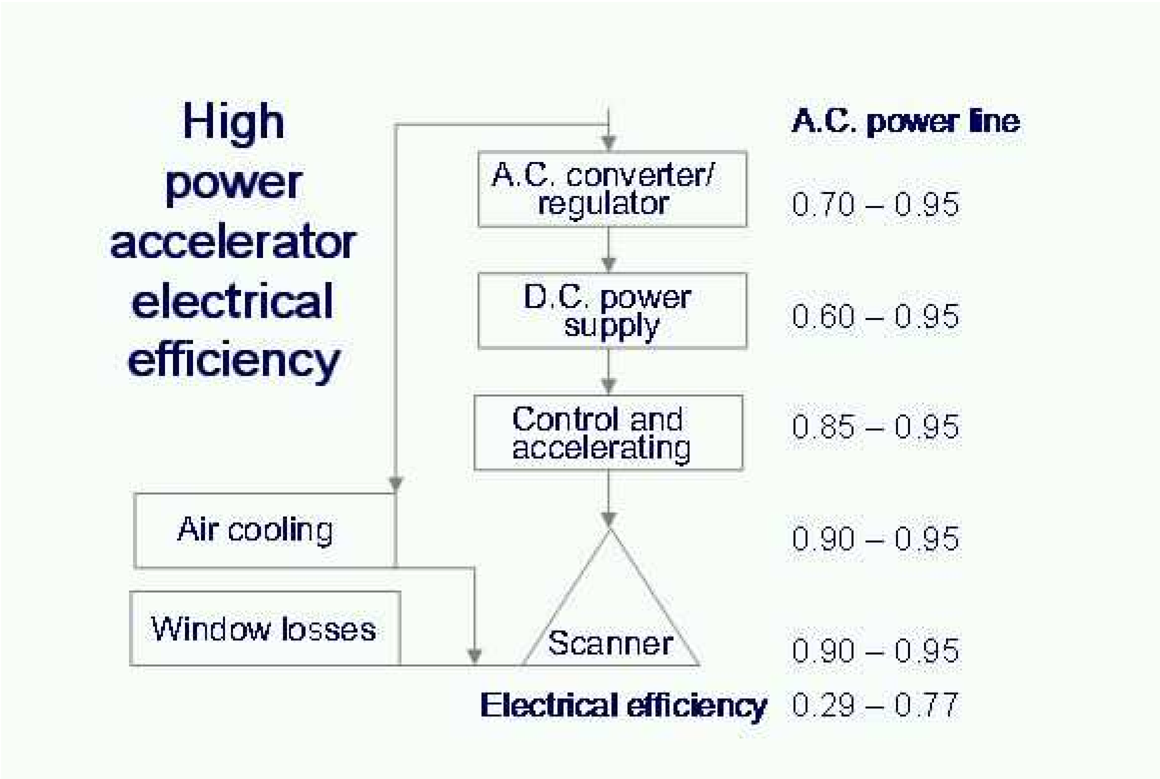

FIG. 1. Block diagram of a high power electron accelerator

2.3. Accelerator price

Influence of accelerators price (beam power cost) on radiation processing technology implementation is well characterized by data presented in Table V. It should be noticed that flue gas treatment technology which has no commercial value requires extremely low beam power investment cost.

TABEL V. RADIATION PROCESS EFFECTIVENESS

Acceptable price of 1 W electron beam power	Type of radiation process	Product characteristics
100-250 $/W	Semiconductors modification	Low dose Small scale High unit price
100-50 $/W	Radiation sterilization	Medium dose Large scale Medium unit price
<2.5 $/W	Flue gas treatment	Low dose Very large scale No commercial value

3. DIFFERENT CONCEPTS OF HIGH POWER ELECTRON ACCELERATORS

The basic principle of any accelerator is that the electric field acts on electrons as charged particles and gives the energy equal to the voltage difference across the acceleration gap. The electric field comes directly from high voltage electrodes or indirectly from the electromagnetic field.

The major difference between different accelerators applied in radiation processing is the method by which electric field is generated. Due to energy range and beam power level the most common constructions for radiation processing are direct accelerators, single cavity resonant accelerators and microwave linacs. The most suitable high power accelerator constructions for industrial scale flue gas treatment process are at present direct power line transformer accelerators. Different constructions of high power accelerators have been described in literature. Some of them could be selected for flue gas treatment process if their manufactures would be able to fulfill all requirements regarding electron energy, beam power, electrical efficiency, reliability/availability according to industrial practice and low price related to beam power.

3.1. CW Linear accelerator

The family of compact modular continuous wave (cw) linear electron accelerator has been designed and tested. The accelerator modules are now capable to accelerate 50 mA average beam current with electron energy increments 600 keV what corresponds to 30 kW beam power [4]. Klystron operated at frequency 2.45 GHz was used. Electrical efficiency of the accelerator based on designed modules amounts 40%. Although high power microwave sources are now available, presented construction does not fit requirements of flue gas treatment process due to relatively low average current and low electrical efficiency.

3.2. Single cavity resonance accelerator

TT 1000 Rhodotron capable to deliver 5 and 7 MeV electron beams with average current intensity of 100 mA has been designed and tested [5]. The electron accelerating concept is based on single cavity which is crossed several times by recirculation electron beam. Beam power up to 700 kW has been obtained with maximum electrical efficiency 55 %. Several beams passing the same cavity concept is under consideration to increase average beam current and maintain high beam power with lower electron energy level. This conceptual design has not been tested yet.

3.3. High power compact transformer electron accelerator

High power compact transformer electron accelerator has been designed and tested at Institute of Nuclear Physic in Novosibirsk, Russia in connection to development of accelerating unit for experiments in the field of high energy physics [6]. Compact power supply operated at 1 MV voltage with power 300 kW and outside diameter 1.2 m was used. The size of power unit was reduced due to applied 1 kHz power line frequency and SF_6 gas isolation. Power supply electrical efficiency of 95 % has been achieved. The power supply was connected to accelerating section by HV feeder with gas isolation. Unfortunately this very promising construction has not been commercialized and there is no evidence about its exploitation performances.

3.4. High repetition pulsed accelerator

Design of the multi-beam accelerator was reported by Dolbilov et al. from JINR, Dubna, Russia [7]. The parameters of the accelerator are as follow:

- Energy 600-700 kV
- Beam power up 300-350 kW
- Pulse current 5 A
- Pulse duration 10-20 μs
- Frequency 10-20 kHz
- High efficiency 95%

- Low energy losses in extraction window.

A coaxial spiral-line resonator serves as a high voltage power supply. Electron beams are generated by a mosaic cold cathode with threshold emission. Cold pyrolitic cathodes are located in such way that electrons emitted from a given cathode go to corresponding window. Threshold level is close to max. voltage and the electron energy dispersion are smaller than 15%. High beam current, high beam power, low cost, high reliability are expected. Unfortunately there is no evidence about industrial application of this interesting construction.

3.5. Induction accelerator

Induction accelerators are capable to deliver high power electron beams at energies of 1-10 MeV. Induction accelerator based on all-solid-state technology (modulator efficiency 85 %) is in operation at Science Research Laboratory, Somerville, U.S.A. [8, 9]. Following parameters have been obtained:

- Electron energy 1.5 MeV
- Pulse duration 50 ns
- Pulse beam current 500 A
- Repetition rate 5 kHz
- Beam power up to 500 kW
- Efficiency: >50 %

Series of experiments were performed at SRL to demonstrate the capabilities of induction linacs for industrial applications. In spite of shown promise there is no commercial proposals regarding to high power industrial induction accelerator with confirmed performances including reliability.

3.6. Coupled-Multiplier Accelerator

A new approach to efficient high voltage generation at MV level has been recently demonstrated [10]. High voltage is produced by a series of modules, each of which consists of a high-power alternator, step-up transformer, and 3-phase multiplier circuit. The alternators are connected mechanically along a rotating shaft driven by electrical motor. Relatively low cost and efficiency 67 % have been reported. The first 1 MV and 100 kW of the coupled multiplier accelerator will be installed at a petrochemical plant and used to treat industrial wastewater. 2 MeV and 200 kW accelerating unit has been designed.

4. ACCELERATORS FOR FLUE GAS TREATMENT

The principal parameters to be achieved for accelerators applied for flue gas treatment in pilot and industrial facility are as follow:

- Electron energy 0.8 – 1.5 MeV
- Beam power 100 – 500 kW
- High reliability for long time operation (6000 h/y),
- Availability >95 %,
- Electron beam cost ~2.5 $/W,
- Electrical efficiency >80 %,
- High current density, low level losses windows,
- Fault protection systems.

Manufacturers of high power transformer accelerators who are interested and capable to participate in practical implementation flue gas treatment technology are listed bellow:

- RDI - Radiation Dynamics, USA (power line frequency transformer),

- Wasik Associates, USA (power line frequency transformer),
- NIIEFA - Sci. Inst. of Electrophysical Apparatus, Russia (power line frequency transformer),
- BINP - Institute of Nuclear Physic, Russia (coreless transformer),
- Vivirad, France (ICT transformer).

5. FINAL REMARKS

Appropriate accelerator selection should be performed to meet all technical and economical conditions for successful process implementation. Power line frequency, high voltage transformers for high power accelerates are at the moment the best solution for flue gas treatment process because of: level of beam power, size, electrical efficiency and cost. It should be noticed that any practical accelerator construction must be compromise between size, efficiency and cost. Best accelerator selection for proper radiation facility design should be performed with possibly:

- Low electron energy,
- High beam power,
- High accelerator electrical efficiency,
- High beam utilization,
- High availability.

Special attention should be devoted to optimization electrical energy consumption for accelerator and auxiliary equipment installed in radiation facility. The electrical efficiency has significant influence on cost of facility exploitation. Reliability/availability of high power accelerator plays critical role for any industrial facility including environmental applications.

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