Application and Economics of Electron Beam Wastewater Treatment

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Abstract. Radiation processing was found effective in wastewater purification and disinfection, and has been investigated in many countries through laboratory scale and pilot scale facilities. This technology can be applied to the treatment of industrial wastewater from textile dyeing industries, papermill and petrochemical processes, and also for the reclamation of effluent from municipal wastewater treatment plant. The facility throughput can be increased and unit cost of wastewater decreased by improvement of electron beam utilization. Higher process efficiency and lower unit cost can be obtained by implementation of lower dose level. The minimum dose depends on characteristics, specific properties and contamination of certain wastewater. Electron energies more than 1.0 MeV are useful for industrial scale plant, such energy provides enough penetration of accelerated electrons into wastewater at admissible hydrodynamic regimes of wastewater flow.

1. Introduction

Radiation processing of wastewater treatment is non-chemical, and uses fast formation of short-lived reactive particles, which are capable of efficient decomposition of pollutants inside the wastewater. For practical treatment of wastewater the radiation processing gives essential conveniences and advantages:

- Strongest reducing and oxidizing agents;
- Universality and inter-changeability of redox agents;
- Variety of paths for pollutant conversion;
- Process controllability;
- Wide choice of equipment and technological regimes;
- Compatibility with conventional methods.

High-energy irradiation produces instantaneous radiolytical transformations by energy transfer from accelerated electrons to orbital electrons of water molecules. Absorbed energy disturbs electron system of the molecule and provides breakage of inter-atomic bonds [1]. Hydrated electron e^-_{aq}, atom H, radicals $^\bullet OH$ and $HO_2^\bullet$ and hydrogen peroxide H_2O_2 are most important products of the fragmentation and primary interactions (radiolytical products)

$$H_2O \xrightarrow{EB} e^-_{aq},\ ^\bullet H,\ ^\bullet OH, HO_2^\bullet, H_2O_2 \quad .$$

High reactivity is characteristic of water radiolysis products [2]. Typical time of their reactions with natural impurities in water is, as the rule, less than 1 micro second. At the same time, reactivity of radiolytical products has quite different principles. Hydrogen peroxide H_2O_2, radicals $^\bullet OH$ and $HO_2^\bullet$ are oxidizing species, however atom H and e^-_{aq} - reducing ones [3]. Simultaneous existence of strong oxidants and strong reductants inside wastewater under treatment is remarkable and important peculiarity of radiation processing. Dominant position among radiolytical oxidants belongs to radical $^\bullet OH$. It has formed at high radiation chemical yield. Oxidation power of $^\bullet OH$ is higher than oxidation powers of conventional industrial oxidants $Cl_2, O_2, HOCl, KMnO_4, K_2Cr_2O_7$ and O_3. The typical rate constants for the reactions of $^\bullet OH$ are from 1×10^7 to 1×10^9 $dm^3 \cdot mol^{-1} \cdot s^{-1}$ [2].

2. Application of Electron Beam in Wastewater Treatment

The first studies on the radiation treatment of wastes were carried out in the 1950s mainly for the disinfection. In the 1960s these studies were extended to the purification of water and wastewater. After some laboratory researches on industrial wastewaters and polluted ground waters in 1970s and 1980s, several pilot plant, including mobile electron beam facility, were built for extended researches in 1990s. Aqueous effluents that can be treated by irradiation fall into two groups. The first includes industrial wastewater, and the second natural and contaminated water (including effluents from municipal plants). The main differences between the two groups are the concentration of pollutants and the level of infection, both of which are higher for the first group of effluents; however the disinfection is main interests for the second group. The treatment of wastewater with low-contaminated wastewater (~100 ppm) is simple, requires low dose (about 1 kGy or less) and gives complete elimination of smell, colour, taste and turbidity. The radiation processing of high-polluted water can require preparing the special conditions. It is to choose the right type for transformation - reduction, oxidation, addition or removal of functional groups, aggregation, disintegration etc.

2.1. Radiation Processing of Industrial Wastewater

For the industrial wastewater, due to the tremendous variety of wastewaters generated by different industries, universal treatment process is not currently possible. Extensive studies have been carried out on the purification of industrial wastewater by radiation processing, although generally on the laboratory and, to a lesser extent, the pilot plant scale. The first full scale application is the purification of wastewater at the Voronezh synthetic rubber plant in Russia. The Voronezh plant has two purification lines, each equipped with an accelerator of 50kW to convert the non-biodegradable emulsifier presented in the plant wastes to a biodegradable form. [3]

Another application is combined radiation and biological treatment in Daegu, Korea [4] A Pilot scale plant for textile dyeing wastewater has constructed and operated continuously since 1998. This plant shows the reduction of chemical reagent consumption, and also the reduction in retention time with the increase in removal efficiencies of COD_{Cr} and BOD_5 up to 30~40%. Increase in removal efficiency after radiation treatment is due to radiolytical transformation of biodegradable compounds in more easily digestible forms. On the basis of data obtained from pilot plant operation, industrial scale plant is under construction. Radiation treatment of textile dyeing wastewater and several dyes are also actively studied in Brazil, Hungary and Turkey [5,6,7].

2.2. Reclamation of Effluent from Municipal Wastewater Treatment Plant

Research activities have demonstrated that inactivation of fecal coli-forms in secondary effluents from municipal wastewater plant can be obtained with doses less than 1 kGy. While conventional disinfectants are adversely affected by the water matrix, radiation processing for bacteria inactivation is generally unaffected by the matrix. Therefore radiation processing has a clear advantage over the existing methods for municipal wastewater disinfection. Reclamation of effluent from municipal wastewater treatment plant is actively studied in Austria, Korea, Brazil, Ecuador and Jordan. In Austria, the effect of oxygen on the radiation-induced inactivation of selected micro-organisms in water has been studied. And cost assessment based on a radiation dose of 1 kGy resulted in total cost of 0.1$/m^3 for a capacity of about 1150 m^3/h for secondary effluents which should be acceptable with regard to the advantages that the radiation induced disinfection provides over conventional technologies. [8] A 99% reduction of micro-biological content of the irradiated water was achieved at the doses of 2kGy in Jordan and to carry out the effective deactivation of nematode eggs, up to 3kGy of irradiation doses are required. [9] Regulations currently exist for E-coli concentrations in secondary effluents in some countries, and such regulations will be adopted by a significant number of countries in the near future and hence radiation processing is a highly attractive technology for meeting such regulations, especially given the advantages compared to conventional technologies, however, at present there is no full scale radiation treatment plant in operation.

2.3. Radiation Induced Removal of Heavy Metal Ions from Water

The toxic metals from industrial effluent streams include heavy metals such as lead, mercury, cadmium, nickel, silver, zinc, and chromium. These heavy metals are accumulated in soil and eventually are transferred into human food chain. Ionising radiation of aqueous solutions generates free radicals, radical ions and stable products as described in the above,
The hydrated electron e^-_{aq} is the strongest reducing agent, and reduced Cr(VI) to Cr^{3+}. [10]

$$e^-_{aq} + H_3O^+ \rightarrow {}^\bullet H + H_2O$$

$$Cr(VI) + {}^\bullet H \rightarrow Cr(V)$$

Cr(V) is unstable and is further reduced to the stable Cr^{3+} ions. And also for the Lead, Cadmium and Mercury, the hydrated electron reduce them. [11,12] The hydroxyl radical (${}^\bullet OH$) is one of the powerful oxidizing species, which lead to transformation of metal ions to the higher valence states [3]. However, due to the fact that normally concentrations of heavy metals in wastewater are very low (ppms), the process seams to be no technically feasible, since trace quantities of reduced metals have to be separated on mechanical way from the wastewater. For higher concentrations chemical (precipitation, ion exchange) or physical methods (membranes, electrolysis) are more feasible from economical points of view.

3. Economics of Electron Beam Wastewater Treatment

Most important factor to control the economics of electron beam wastewater is the cost of electron accelerator in use. Accelerator manufacturers produce many kinds of electron accelerators with energy range from 0.5 to 10 MeV and beam power range from 50 to 400 kW. For flue gas treatment, electron energies around 0.7 ~1.0MeV is enough to use, but electron beams at energy more than 1.0 MeV are useful for wastewater treatment. Such energy provides enough penetration of accelerated electrons into wastewater at admissible hydrodynamic regimes of wastewater flow. The accelerators with beam energy more than 5 MeV are being produced at low beam power (less than 50 kW). Low beam power is enough acceptable for experimental and pilot plants but not for large-scale treatment of industrial uses. Therefore, the medium energy accelerators obtained the maximum practical use for wastewater treatment. The beam power of such accelerators reaches 400 kW and there are several projects for production of accelerators at beam power up to 1 MW. The basic criterions of accelerator for environmental application are as follows:

- High beam power to increase productivity and reduce unit operation cost,
- High electrical efficiency to reduce exploitation and unit operation costs,
- High beam utilization to increase productivity and reduce unit operation cost.

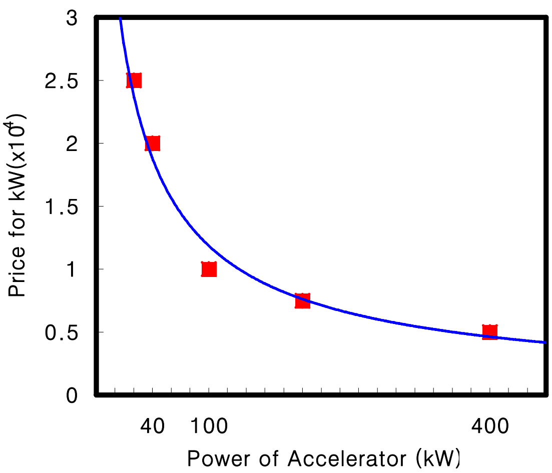
TABLE I: SELECTED ACCELERATORS FOR RADIATION PROCESSING

Manufacturer (Model)	Energy [MeV]	Current[mA]	Power [kW]	Price [M$]	Cost [$/W]
IBA, Belgium (UHF)	10	15	150	6.1	40.7
RDI,U.S.A. (DC)	5	50	250	4.9	19.6
NHV, Japan (DC)	5	30	150	5.0	33.3
Vivirad, France (DC) (under development)	5	200	1000	4.4	4.4
BINP, Russia (UHF)	5	10	50	1.2	24.0
BINP, Russia (DC)	1	400	400	2.0	5.0

Basic parameters of selected accelerator constructions are included to the TABLE I. As is shown in FIG. 1, the cost of accelerators are governed by their beam powers and the accelerator with the highest power has the lowest cost for unit power generation and most economical to apply in environmental application.

3.1. Capital Cost and Operation Cost of Industrial Plant

For the reclamation of effluent from the municipal plant, on the basis of the data obtained by several investigators and the economical evaluation, the suitable dose is around 0.2 kGy for the flow rate of 100,000m^3 effluents per day. The cost assessment of radiation processing plant with e-beam is accomplished based on 0.2kGy and 400kW electron accelerator. Cost of such high power accelerator is around 2.0M$ at market and building, piping, other equipment and construction works could be estimated 1.5M$. Even by considering the additional cost for tax, insurance and documentation as 0.5M$, the overall capital cost for plant construction and operation cost are approximately 4.0M$ and 1.0M$ as stipulated in TABLE II and TABLE III.



Power (kW)	Price (M$)	Cost for each kW ($10^4$$)
20	0.5	2.5
40	0.8	2.0
100	1.0	1.0
200	1.5	0.75
400	2.0	0.5

FIG. 1. Unit cost comparison of typical accelerators

TABLE II: CAPITAL COST FOR INDUSTRIAL PLANT (UNIT: M$)

	Cost	Remarks
Accelerator - 1MeV, 400kW, double window	2.0~2.5	Cost for Land, R&D, Approval from Authorities are not included
Water reactor & other Raw Material	1.0~1.5	
Installation cost – welding/piping/inspection etc.		
Design		
Shield Room & Construction works		
Others - transportation, tax, insurance etc.	0.5	
Total	4.0~4.5	~ 4M$

Above estimation doesn't include the cost for land, R & D and the cost for the approval form authorities. Expected construction period includes 11 months in civil and installation works and 3 months for trial operation. To estimate the operation cost, the electricity consumption of accelerator and other equipment is calculated as 500kW (80% efficiency) and 300kW to the total of 800kW. Based on the year round operation (8000hr/yr), it costs 320,000$/yr when the cost of electricity (kWh) was assumed to be 0.05$. The labour cost of operator is calculated on 3-shift work and is approximately 100,000$/yr in total. Therefore, the actual operation cost for 100,000m3/day plant comes up to around 1.0M$/yr including the interest and depreciation of investment and is approximately 0.12$ in construction and 0.03$ in operation for each m3/day of wastewater. [13]

3.2. How to improve economies of wastewater treatment

The key to the successful application of electron beam in environmental protection is how to manage the economies in its application. To compete with other processes in economic evaluation, the electron beam system should consider following points;

- Reduce the required doses
- Improve efficiencies
- Reduce the cost for electron beam facilities

For the wastewater with low pollutants level such as contaminated ground water, effluent from municipal plant, the treatment is simple, requires low dose and gives complete elimination of smell, colour, taste and turbidity with not more than several kGys. The high-polluted water, like industrial wastewater, may require preparing the special conditions. To reduce the required doses, to choose the right types of transformation - reduction, oxidation, addition or removal of functional groups, aggregation, disintegration etc. and application of useful additives or addition of radical enhancer/reducer is considerable.

TABLE III: OPERATION COST FOR INDUSTRIAL PLANT (UNIT: k$)

Items		Cost Increase by Introducing E-beam	Remarks
Operation Cost	Invest (k$)	(4,000)	
	Interest	240	6%
	Depreciation	200	20yrs
	Electricity	320	800kW
	Labour	100	3 shift
	Maintenance, etc.	80	2%
Total cost		940	~ 1M$/yr

4. Summary

Rapid population growth with industrialization, urbanization and water-intensive lifestyles results in severe problems in wastewater management. At present the wastewater treatment with radiation processing has not wide application and spreads less than conventional methods. However, the pilot plants and industrial application show that radiation processing can occupy the quite essential place at future. Already now the radiation processing and its combination with conventional ones provide noticeable economy of time, area and industrial power to wastewater treatment. Continuous reinforcement of ecological standards is additional motivation for elaboration and industrial application of radiation processing. Propagation of radiation processing can give improvement for environmental protection as well as essential influence on industrial development.

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