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POTENTIAL OF HIGH ENERGY ELECTRON BEAM TREATMENT FOR THE HIGHER PULP YIELD AND ENERGY SAVINGS


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Abstract

It is well known that paper industry is highly energy intensive industry. Presently, Indian paper industry is trying hard to reduce this input in every possible way for mere survival and sustainability of paper production to meet the demand. The electron irradiation as a pre treatment of fiber is a potential mean for reducing the specific energy consumption to a considerable extent. The technology of electron irradiation to wood has been recently investigated and appears to be quite encouraging. However, the results of successful attempts are limited to only laboratory and pilot scales. In this present paper, the success story of electron irradiation based pulping has been highlighted.

From the literature survey, it has been found that this new technology has not been explored yet in large scale for pretreatment of non-wood fibers which are largely used in Asian countries like India and China. This technology can be applied to boost the Indian pulp and paper industry in terms of energy savings and increased production due to higher yield. The details of technology along with necessary equipments, method, time and depth of exposure of electron beam, and various parameters such as electron beam intensity, frequency etc. for electron irradiation, and their effects are discussed.

Keywords: wood, bagasse, electron beam treatment, irradiation, irradiation systems.

1.0 Introduction

On the basis of raw material, paper mills can be classified into three major categories as wood based, agro-resides based and recycled fiber based [1]. Wood and other fiber raw materials are mainly composed of cellulose, hemicelluloses, lignin fraction and other constituents. Only carbohydrates are necessary in papermaking process. Lignin does not contribute to strength properties of paper, but it consumes more chemicals in the bleaching of pulp. Wood can be softwood or hardwood. On the basis of chemical composition, softwoods have high lignin content (25-32 %) than hardwoods (18-25 %) and also have longer fibers. Both softwoods and hardwoods have nearly the same cellulose content about 40-45 % [2]. Conventional methods of pulping are more energy intensive resulting in high pollution load in effluent and very low pulp yield. This requires the search for new pulping methodology for higher yield, lower pollution load and lower specific energy consumption. One of the methods which have been recently explored is the pretreatment of fibers by electron beam irradiation.

2.0 Irradiation Technology

High energy electron irradiation pretreatment of wood chips such as spruce, pines has been proven to enhance the yield and other properties of paper when wood chips were cooked at a high kappa number [3]. The electron beam irradiation has broken down the larger molecules into smaller molecules. The cross linking between the smaller molecules and other constituents of the wood has modified the properties of the paper than unirradiated pulp [3]. The cross-linking may facilitate easier defibration of the cellulose fiber without much destruction to the physical properties. It has also been found that freeness has decreased with the increase in the irradiation dose which indicates the defibration was easier on the irradiated wood than unirradiated. It has been found that the irradiation can modify the lignin structure as well as cellulose and hemicelluloses also. Modified lignin was difficult to solublize because it has resistant to alkali. Therefore the mechanical defibration of the irradiated wood was preferred to reduce the chemical charge in cooking. Cooking time was also shorter than that for unirradiated pulp due to modification of lignin [3]. Ultrasonic treatment of cellulosic pulp fibers also has been used to increase the pulp strength properties [4]. It has been proven that the pretreatment of gamma irradiation has altered the structural and chemical properties of the lignocellulosic material [5, 6].

2.1 Electron beam source and exposure methods

Electron beam has been produced through various means such as VAN de GRAFF or microwave or radio wave radiation (KLYSTRON type) [7, 8]. These electron sources produce energy of thousands of volts. Wood chips were subjected to electron irradiation by passing chips on a conveyor belt or pneumatic system. In belt conveyer system, wood chips were treated on both sides to achieve the optimum exposure on the both sides of the chips. There are two types of systems that could be used for electron treatment at the industrial level viz. pneumatic system and belt conveyer system.

The pneumatic system for the treatment of wood chips has been developed by David Free in 1972 and design of corresponding facility is patented [7]. The equipment used for irradiation in pneumatic system is shown in Fig. 1.

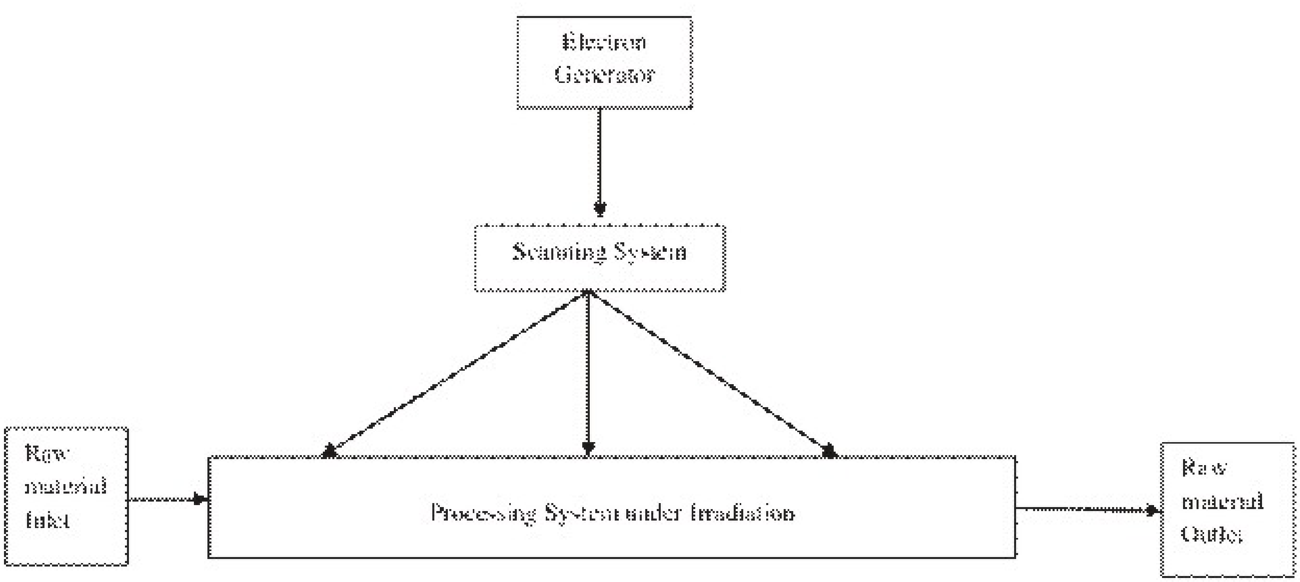

Figure 1: Schematic diagram of for generation of electron beam pneumatic system

The irradiation pneumatic system generally consists of some important elements such as electron generator, scanner with titanium wall, and conduit with trapezoidal cross-section, pipeline, and coolant fluid. The pneumatic system has the advantage over belt conveyer because the belt conveyor system treats only one side but the former treats all sides in a single exposure of irradiation (Table 1). The comparative description is given in Table 1.

Table 1: Comparison of irradiation treatment systems [7, 9]

System	Advantages	Disadvantage
Pneumatic system	Purpose of trapezoidal shape is to provide effective exposure of wood with high-energy electron beam. Provide uniform coverage area throughout the conduit. Chips will continue rotating in the pipe line throughout the conduit six times while travelling six feet length of conduit, due to high velocity of the pneumatic conveyer system. This is called "magnus" effect (spinning of chips). It may irradiate all sides to maintain the uniformity.	Velocity of 30 m/s is required for conveying the wood chips. Over-heating of system may occur.
Belt conveyer system	Equal exposure on both sides of the chips. Less energy is required. Used for low irradiation dose.	All sides are not possible to irradiate.

The belt conveyer system has been used for treatment of wood chips as well as pulp. The researchers' group at Atomic Energy of Canada's Whiteshell Laboratories has successfully developed and utilized electron irradiation facility for the treatment of wood pulps [9]. This device is capable of generating power up to 10 MeV. The facility used for irradiation treatment of wood pulp is shown in Fig. 2.

The belt conveyor facility with TT 300 accelerator operated by Synergy Health Radeberg GmbH, Germany has been used for irradiation. This device is capable of accelerating electrons up to 10 MeV [10].

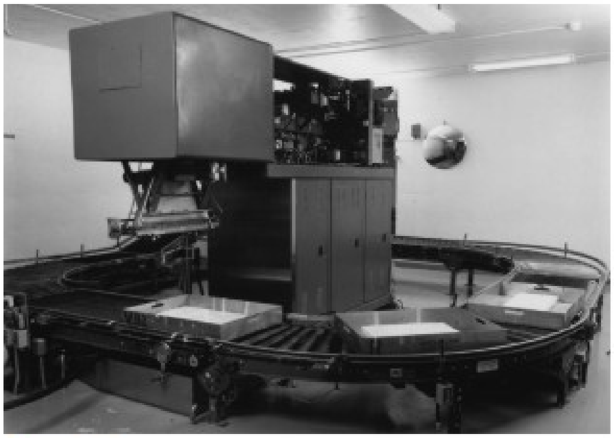

Figure 2: Electron treatment of pulp using Acsion's I-10/1 accelerator (belt conveyer system) [9]

2.2 Factors affecting irradiation treatment

1) Electron beam intensity: average beam current, distribution of electron beam intensity and pulse duration.
2) Scanning system: mode of operation, magnetic system and frequency of scanning system.
3) Cooling system: geometry of the cooling system, thickness and composition of cooling agent.
4) Regimes of the irradiation: irradiation of rotated target and one or two-sided irradiation on moving conveyor [11, 12].

The main parameters for irradiation are absorbed dose and rise of temperature.

The absorbed dose is defined as the absorbed energy per unit mass. A unit of absorbed dose is kGy (kilogray) [13].

$$\text{Absorbed dose } D = \frac{dE}{dM}$$

where dE = absorbed energy (mean energy), dM = mass, D in terms of kGy or Joule per kg. Temperature rise: The rise of temperature of the irradiated material during the irradiation is proportional to the absorbed dose. Temperature rise in Kelvin (K) is given

$$\Delta T = D/c$$

where ΔT = temperature rise, K, D = absorbed dose, kGy, c = thermal capacity (J/gK).

2.3 Measurement of absorbed dose

The softwares known as XR-soft, ModeSteB and Radiation –Technological Office (RT-Office) have been used to reduce the complexity of measurement of absorbed dose and temperature distribution within the irradiated material [12, 13, 14]. Hence, XR-soft has become the accessible tool for the determination and optimization of the absorbed dose (dosimetry) [12].

2.4 Dosimetric analysis

Dosimetry works on the principle of the measurement of the electric current from the irradiation. This electric current is proportional to the dosing rate of the irradiation. Semiconductor material in the dosimetric stack film consist of 1 to 60 plates to form a dosimetric film, generates electric current when radiation hits the film and generates measurable electric current [13]. A film should be perpendicular to the incident electron beam.

The absorbed dose is proportional to the electric current (I) and inversely proportional to the web speed (v).

$$\text{Absorbed dose} \quad D = KI/v$$

where I is in mA and v is in m/min and absorbed dose in kGy.

Two types of the geometrical models have been used to measure irradiation dosimetry. 1) Product is irradiated on moving conveyor. 2) The product is irradiated in rotating cylindrical chamber in front of the electron beam. It has been reported that 38.5 cm was the optimum thickness for the maximum power utilization during treatment for the X-ray with the efficiency of 48 %.

2.5 Control of irradiation

Attenuator blocks are used to control the irradiation dose. Attenuators act by absorbing or scattering of the radiation that are in excess of the dosing limit. Absorption of excess irradiation depends on the thickness, density, and atomic weight of the attenuator. Some of the attenuator's materials are lead bricks, lead clad building material, lead laminated panels, leaded glass, sheet and bricks, leaded plastics.

The effects of irradiation treatment in the various raw materials are given in the table 2.

Table 2: The mechanisms of radiation treatments studied

Treatment	Mechanism
Gamma irradiation [15]	Modification of lignin structure; intermolecular cross-linking
Electron beam [16]	increase the surface area of cellulose available for bonding(fibrillation)
Electron beam [17]	Polymerization of cellulose pulp
Electron beam [18]	Destruction of detrimental substances and increase yield
Electron beam [19]	Polymerization, chain scissoring, cross linking
Electron beam [9]	Reduced pollution load, elimination aging, increased the yield
Gamma irradiation [5]	Structural changes; reduced crystallinity
Electron beam [20]	Chain scissoring
Electron beam [21]	Depolymerization of cellulose
Electron beam [22,23]	Depolymerization and chain scissoring
Electron beam [24]	Modification of cellulose

The effects of irradiation treatment have occurred due the high energy of the irradiation, which includes the modification of lignin structure, polymerization or chain scissoring of the carbohydrate or lignin structure. However, the effect depends on the duration, dose and type of irradiation, and exposure and many others.

3.0 Literature results and discussion

In the following paragraphs the results are reproduced which are reported by some investigators in their patents and publications [8, 25]. Table 3 shows the comparison of the treatment dose and pulping methodology for the various types of raw materials such as beech, western hemlock, spruce and pines.

Table 3: Irradiation treatment of various raw materials

Parameters	Bergstrom and Ernst, 1976 [8]	Fischer and Ringel, 1976 [25]	Bergstrom and Ernst, 1976 [8]
Raw material	Western Hemlock (*Tsuga heterophylla*)	Beech	Spruce/ Pines/Bagasse
Radiation dose, megarads	>1 (0.5)	0.1-1.0	-
Frequency, MHz	-	-	10-300000
Potential, kV	500	200-1500	-
Current, mA	20	0.3-30	
Intensity, megajoule/kg	-	-	0.5
Time of exposure, sec	-	0.06-180	0.1
Cooking condition	Chemical 13 % EA Temperature,165-170 °C, Time ,180 min at maximum temperature	Sulfite	Thermo-mechanical at high temperature and pressure by irradiation
Kappa Number	90	10	-
Yield, %	47.9	-	96
Freeness, mL CSF	485	-	150
Breaking length, km	-	-	6
Tear factor	93	-	-
Comments	-	Lignin content decreased	Free cellulose fiber

Table 4: Comparison of irradiated and unirradiated pulping of wood Western Hemlock (*Tsuga heterophylla*) and effect on pulp properties [8]

Parameter	Unirradiated pulp at 60 kappa no	Unirradiated pulp at 90 kappa no	Irradiated pulp (0.5 megarads) at 90 kappa no.	Benefits
EA, %	14	13	13	-7.7%
Yield, %	44.2	40.5	47.9	+15.44%
Freeness, mL CSF	524	604	485	-
Kappa number	60	90	90	—
Burst index, kPa.m²/g	9.80	9.10	9.70	+
Tear index, mNm²g	11.78	12.08	9.20	-
Breaking length, km	10.69	10.40	10.64 10400	+
Brightness at 457 nm	14.5	11.5	14.1	+

Table 5: Effect of amount of irradiation on pulp properties (8)

Amount of Irradiation, megarads	Kappa no.	Freeness, mL CSF	Tear index, mNm²/g	Tensile index, Nm/g	Burst index, kPa.m²/g
0	44	435	12.27	10.65	9.40
0 refining	38	404	12.07	9.81	8.11
0.20	34	384	10.10	9.59	8.31
0.50	44	299	9.00	11.61	10.09
1.0	41	186	8.02	11.99	10.20
1.0 refining	38	157	8.11	12.32	10.20

It has been found that the high-energy electron treatment resulted in the sudden increase in the temperature within 0.003-3 min. This resulted in the immediate vaporization of the water in the material at high temperature, lignin is softened and able to free the cellulosic fibers. Tables 4 and 5 indicate that electron radiation is able to improve the strength properties than the unirradiated sample and also reduce the chemical consumption. 7 % reduction in the chemical consumption results in about 15 % increase in the yield. Without irradiation, 7 % decrease in the chemical charge results in about 9 % decrease in the pulp yield. Thus, it shows that the electron irradiation increases the pulp yield and helps us to reduce the chemical consumption that will reduce the burden on the chemical recovery. Electron irradiation has decreased the lignin content by fragmentation of the lignin structure which decreased kappa no., increased brightness of the pulp and lowered chemical consumption during the bleaching stages [6, 26, 27].

However, the investigators have not shown the results graphically. In this present study, the results based on the limited data of pulping are plotted in graphs to more clearly understand and to better interpret the effects of various parameters on strength properties and freeness of pulp. The strength properties studied were mainly tear, tensile and burst index. These are explained as under:

3.1 Effect of irradiation dose on strength properties of pulp

Strength properties (tear index, tensile index, and burst index values) have been plotted as a function of amount of irradiation in Fig.3. It is evident from the figure that the burst and tensile index increases linearly with increase of amount of irradiation but tear decreases due to the chain cleavage. It is an expected trend even for pulp without treatment of electron irradiation. Increased tensile and burst strength are indicating irradiation has increased fibrillation of fibers which make good bonding.

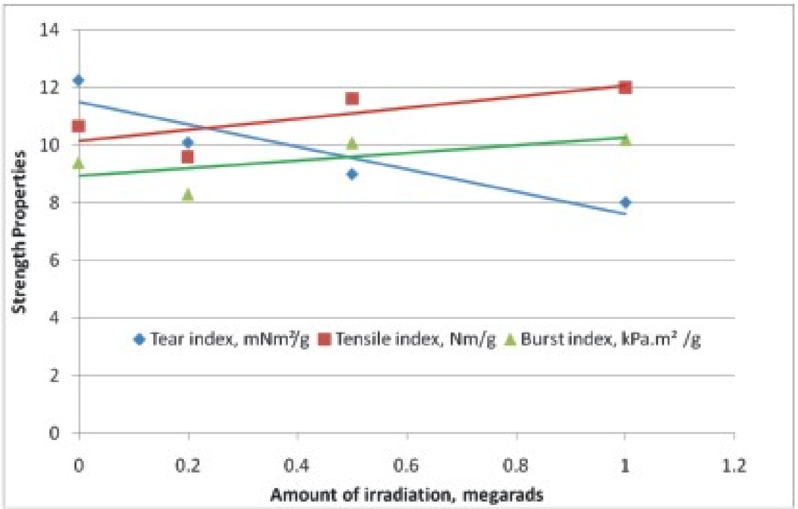

Figure 3: Effects of irradiation dose on strength properties of pulp [8].

3.2 Effect of irradiation on freeness of pulp

The Canadian Freeness values (CSF) as a function of amount of irradiation is shown in Fig. 4 to examine the effect of amount of irradiation on defibration efficiency.

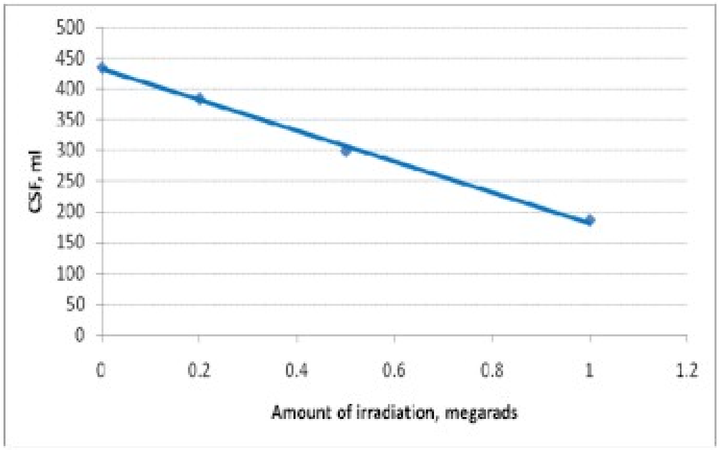

Figure 4: Effects of irradiation dose on freeness of pulp [8]

The figure reveals that as amount of irradiation increases the CSF level decreases. This further indicates that more defibration takes place to decrease the CSF value i.e. pulp has slower drainage tendency. Therefore, it concludes that irradiation of electron beam can improve the beating and refining of the pulp fiber. This in turn may lead to the better formation of the fiber on the wire and good strength properties of the fiber due to the good fiber bonding.

3.3 The effect of irradiation on specific energy consumption in mechanical pulping

Recently, the work of application of irradiation technology has also been extended for examining potential of energy saving in mechanical pulping at TU Dresden, Germany, Experimental investigations in laboratory, pilot plant, and full scale trials have been made [10, 28, 29]. A comprehensive review on these works is available [30]. It is depicted that the electron irradiation has the possibility of implementation ETMP methodology to TMP for increasing yield and energy savings (28). The trials have also been taken in full-scale plant with spruce to investigate the extent of energy savings and high yield. The specific energy consumption v/s freeness value with respect to time is

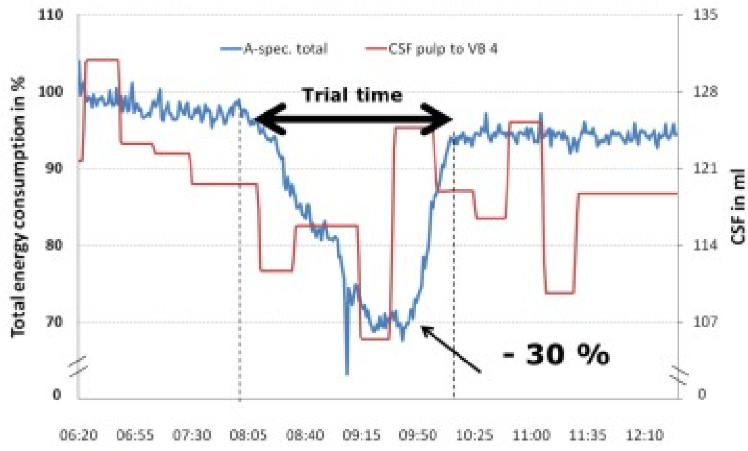

Figure 5: Total energy consumption of the refiners in large-scale trials [29]

It is evident from the figure that irradiation of raw material, e.g. wood with irradiation dose of 30 kGy significantly exceeds the chemical bonding energy and the ionization potential of molecules [27]. This irradiation treatment was resulting in an energy saving of 30 % on TMP production [28, 29]. It is assumed that irradiation mechanism occurs only in atomic envelope, not in the atomic nuclei. So there is no chance of any hazard during processing and handling of raw material after treatment.

3.4 Proposed strategy for non-wood fiber

This novel technique can be applied to non-wood fibers including bagasse. Bergstrom and Ernst in 1976 indicated that method of irradiation for spruce can also be possible for irradiation to bagasse and also described in his patent but no detailed analysis has been given [8].

In our opinion, bagasse has the almost same fiber length, as hardwood while lignin content is comparatively less. It also gives similar yield [30]. However, bagasse is a bulky material than hardwood. Therefore, it is suggested that the following modifications are required for treating the bagasse.

1) Equipment size should be large to accommodate the same amount as wood.
2) Bagasse being a bulky material it is necessary to determine the actual dose, depth and time of exposure for continuous irradiation treatment for this raw material..
3) Determination of the efficiency of electron beam treatment in estimating power utilization for bagasse.

4) Electron irradiation mapping and routine dosimeter for homogeneity of dose distribution and process stability. The dose difference should be low.

5) Optimization of energy consumption for irradiation dose for bagasse in order to compare with those for wood which was 60 kWh/t for 30 kGy [10].

This needs further detailed investigation in regard to benefits accrued out of electron irradiated pulping of bagasse of Indian origin. More importantly, economic feasibility analysis has to be made not only for bagasse but also other wood based raw materials which have already been investigated.

4.0 Conclusion

Based on the detailed review of the emerging pulping technology with pretreatment by high-energy electron irradiation the following conclusions can be made. No work has been done till today regarding irradiation of bagasse fiber. Only few data are available on irradiation of hardwood and softwood determined by few investigators in foreign countries and most of these works have been patented. No industrial scale trial is documented in literature except the work at TU Dresden on mechanical pulping for TMP.

From the detailed study, it can be inferred that it is possible to produce bagasse pulp with high yield and good strength properties by the pretreatment with electron irradiation. The high-energy electron irradiation as a pretreatment prior to the production process can reduce the cooking time for the same kappa number of the final pulp. This can also accelerate the digestion process, increase yield, reduce the excessive bleaching chemical demand and improve the strength properties.

Further, it is revealed from patent information that 7.7 % decrease in chemical charge results in 15.4 % increase in yield for western hemlock wood chips. It is expected that similar results can be obtained for irradiated bagasse.

Detailed experimental and theoretical studies are required to establish economic feasibility of electron irradiated technology application in pulping and papermaking processes.

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