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Measurement of residence time distribution of liquid phase in an industrial-scale continuous pulp digester using radiotracer technique

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HIGHLIGHTS

- Radiotracer experiments were conducted to measure RTD of liquid phase in a pulp digester
- Mean residence times of white liquor were measured
- Axial dispersion and tanks-in-series models were used to investigate flow patterns
- Parallel flow paths were observed in first section of the digester
- Optimized flow rates of biomass and liquor were obtained

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ABSTRACT

A series of radiotracer experiments was carried out to measure residence time distribution (RTD) of liquid phase (alkali) in an industrial-scale continuous pulp digester in a paper industry in India. Bromine-82 as ammonium bromide was used as a radiotracer. Experiments were carried out at different biomass and white liquor flow rates. The measured RTD data were treated and mean residence times in individual digester tubes as well in the whole digester were determined. The RTD was also analyzed to identify flow abnormalities and investigate flow dynamics of the liquid phase in the pulp digester. Flow channeling was observed in the first section (tube 1) of the digester. Both axial dispersion and tanks-in-series with backmixing models preceded with a plug flow component were used to simulate the measured RTD and quantify the degree of axial mixing. Based on the study, optimum conditions for operating the digester were proposed.

1. Introduction

The Indian paper industry is one of the leading industries in the world with an approximate share of 2.6% of the global production. Currently, there are 813 paper mills in India based on different types of raw material such as wood, bagasse, agro residue (wheat straw, rice straw, etc.) (Jain, 2015). Traditionally, wood was the only raw material used for paper production but due to the excessive exploitation of forest and environmental concern, wood may not be the right choice for paper production. Hence the alternatives of wood are bagasse, cotton, reed, hemp, agro residue etc. In India, around 14 paper mills are using wood out of 850 paper mills (Bajpai et al., 2004a). The worldwide demand of paper is increasing day by day at the rate of 4-5% per anum and the estimated demand in 2025 would be 21.94 million tons in India (Jain, 2015). The paper production rate in 2006-2007 was 5.9 million tons against the installed capacity of 7.6 million tons (Szabo et al., 2009).

The paper manufacturing process requires wood chips or agro residue raw material. The washed and dust free raw material is directly fed to a pulp digester and converted in to pulp using

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chemical pulping or mechanical pulping methods. The chemical pulping is the most popular pulping method used in the paper industry (Sixta, 2006). In this method the raw material (wood chips/agro-residue) and alkaline solution (white liquor) react in the pulp digester at elevated temperatures of 170–176 °C and high pressure 7-8 kg/cm^2 (Pougatch et al., 2006). At high temperature and high pressure the delignification process takes place. In the delignification process, the natural binding material lignin gets dissolved in the white liquor and the cellulose fibers are separated as pulp. The extent of this delignification is expressed by a Kappa number (K), which is a measure of the residual lignin content in the pulp. The main objective of every pulping process is to minimize the variation in K and produce pulp of uniform quality. The pulp digester is the heart of the paper industry and of capital intensive. On the basis of the operation, the digester can be classified as a batch or continuous type. Traditionally, the batch pulp digesters are commonly used in industry for pulp production. In batch operation, raw material is fed to the digester vessel once and white liquor is continuously re-circulated. After 5–6 hours of operation, the natural binder lignin gets dissolved in the white liquor and cellulose fiber lay by in the form of pulp. The obtained pulp is drained out from the pulp digester and is ready for the next batch. The batch pulping process requires a number of digesters to produce the pulp of total capacity of the mill. Conversely, the continuous digester provides continuous pulp production, i.e., the inflow and outflow are continuous. The continuous operation reduces the raw material and pulp storage requirement which results in economical gain (Sixta, 2006).

The performance of a pulp digester has a great impact on product yield, product quality, overall operating cost and waste generation (Bajpai et al., 2004b). The optimized operating conditions may increase the performance of a pulp digester i.e. improved product quality, increased yield, reduced waste and lower operating cost. During the continuous digester operation, malfunctioning can be expected to occur, such as leakage, fouling, channeling, bypassing, backmixing etc. The malfunctioning and abnormalities of a digester cause deleterious effects on digester operation and may result in inferior pulp quality, improper digestion, energy wastage and high waste generation. These malfunctioning and abnormalities of the pulp digester can be explained or identified with the help of studies of the hydrodynamic behavior of the digester.

The available literature indicates that very limited studies have been conducted to explore the hydrodynamics and mathematical modeling of a pulp digester (Amirthalingam and Lee, 1999; Ding et al., 2007; Doyle and Kayihan, 1999; Pougatch et al., 2006; Wisnewski et al., 1997). Initially a Purdue model was developed by Smith and Williums (1974). Further an extended version of the Purdue model was developed for a continuous pulp digester. The dynamic response and steady state profile of the digester were compared with the previous version of the Purdue model and interpreted for process design modification, optimization and control of the pulp digester (Wisnewski et al., 1997). Another model based on the momentum and mass balance was proposed and used to simulate the process of pulp digesters or similar types of chemical reactors (Pougatch et al., 2006). Furthermore, the K profile for a continuous digester was studied and observed. The significant variations in Kappa number were observed which may be controllable (Doyle and Kayihan, 1999). Subsequently, the governing parameters of a simplified linear model were identified for continuous pulp digester (Ding et al., 2007). The subspace identification technique was also tested on a pulp digester for model formulation and testing (Amirthalingam and Lee, 1999). Another model describing the operational difficulties occur during the transition from hardwood to softwood and the interaction between reaction kinetics along with thermal hydraulics (Bhartiya et al., 2003). Measurement and analysis of residence time distribution (RTD) of process material is one of the main approaches to identify malfunctioning and to investigate flow dynamics of industrial process systems (Danckwerts, 1953; Levenspiel, 2004). Radiotracers are widely used to measure RTD of process fluid in industrial scale-systems due to their certain advantages namely physicochemical compatibility, online measurement, high detection sensitivity, limited memory effect on process (Charlon, 1986; IAEA, 1990; Pant, 2000; Pant et al., 2001; Pant and Yelgoankar, 2002; Ramirez and Cortes, 2004; Din et al., 2009; Pant et al., 2009; Kasban et al., 2010; Dagadu et al., 2012; Pant et al., 2012; Pant and Sharma, 2015). To the best of the authors's knowledge, there is no study reported in the literature on measurement of RTD of a pulp digester using tracer techniques. The present paper reports a radiotracer investigation in a continuous pulp digester in a paper industry.

2. About the digester and pulping process

The schematic diagram of the continuous pulp digester used for chemical pulping from wheat straw is shown in Fig. 1. The digester consists of three horizontal cylinders, each of diameter 1.450 m that are connected in series by a vertical neck which transports the pulping material from one cylinder to the next. The horizontal cylinders are fitted with a separate screw conveyor to transport the pulping mixture. The biomass feed is fed to the digester by a high pressure screw feeder at the inlet of the first cylinder of the digester. The white liquor, which is a mixture of various chemicals used for the pulping process and is fed at the inlet of the first cylinder of the digester with the help of a feeding pump. The sodium hydroxide is the key component of the white liquor and is present in 8.28% (w/w) in the solution. To prevent the degradation of the cellulose fiber, sulfur as sodium sulfite is used in very small quantity 0.44% (w/w). Sodium carbonate is also present in a trace amount of 0.88% (w/w) in the white liquor whereas the sodium chloride is present in 2.20% (w/w). The steam is continuously and simultaneously injected at three different locations of each cylinder at high temperature and pressure through steam nozzles. The injected steam maintains the pulping temperature at 157–169 °C and 5.39–6.45 kg/cm^2 pressure throughout the digester.

In the present study, agro waste i.e. wheat straw was used as feed material. Wheat straw is a complex mixture of lignin, cellulose and hemicelluloses as three main components, and a small amount of soluble substrates (also known as extractives) and ash like other biomass of lingo-cellulosic composition. The overall chemical composition of wheat straw might slightly differ depending on the type of wheat species, soil, climate and cultivation conditions. The wheat straw contains 32–40% (w/w) cellulose, 20–25% (w/w) hemicelluloses and 15–20% (w/w) lignin. The wheat straw obtained from farmers was cleaned, washed and subsequently soaked in water for 36-48 hours for softening of the biomass. The soaked wheat straw with the approximate consistency of 45–47% is the ideal for digestion process. Then it is fed to the digester along with white liquor. The feeding process is crucial in the pulping process because we have to feed the solid / semi-solid material at a high pressure of 7 kg/cm^2 and high temperature of 170 °C. To overcome this difficulty, a screw-feeder is used which compresses the biomass and develops a counter pressure of ($>$ 7) kg/cm^2. During the feeding process, the screw feeder reduces the moisture content of biomass up to 10%. A high pressure white liquor feeding line injects the white liquor in the digester near the screw feeder inlet section. The high pressure superheated steam is also injected at multiple points in the three tube continuous digester. The injected steam maintains the operating temperature of 155–170 °C and operating pressure of 5.39–6.45 kg/cm^2.