ELECTRODIALYSIS TREATMENT OF EMBILIPITIYA BLACK LIQUOR

by

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Abstract

A new type of electrodialyzer unit to fractionate the Embilipitiya black liquor into sodium hydroxide, lignin and organic acids has been proposed and experimented. Lignin deposition on, and the consequent damage to, the anode-side cellophane membrane that are generally associated with black liquor electrodialysis have greatly been minimized in the proposed unit. Also, bubbling of liquor in the anode compartment has completely been eliminated. Even with the use of an ordinary membrane, such as cellophane, the cathode compartments of the proposed unit yield sodium hydroxide solutions of about 0.1N strength. Lignin which has a very high fuel value can be isolated from the end products of electrodialysis by simple filtration. Most importantly the polluting black liquor, upon electrodialysis followed by filtration, yields a colourless liquor with a pH of 6 and a TDS of 0.2 g /l.

1.0 Introduction

Black liquor is a liquid effluent produced in pulp mills that are similar to the one in Embilipitiya, Sri Lanka, where sodium hydroxide is used to pulp the raw material for paper. The raw materials in the Sri Lankan case are mainly rice straw and sometimes wood. Black liquor is rich in valuable chemicals such as sodium, derivatives of lignin, and low molecular weight polysaccharides (Ray et al. 1992). Black colour of the waste liquor is owing to the presence of lignin which is isolated from the raw material during the pulping process in which the raw material is cooked with sodium hydroxide, known also as caustic soda, at specified pressure and temperature. In this soda-pulping process, lignin in the raw material is converted into sodium lignate which exists in black liquor as sodium ions and lignate ions. The concentration of the inorganic ions in black liquor, which are mainly sodium ions, is quantified by measuring the electrolytic conductivity of black liquor using the conductivity meter Hach 44600.

The electrolytic conductivity of black liquor samples from the Embilipitiya pulp mill ranges from 19 to 30 mS/cm which indicates the presence of considerable amount of dissolved solids in black liquor. Total dissolved solids, TDS, of black liquor is about 64 g/l (CISIR 1994). Black liquor has a pH of about 10 when measured by the pH meter TOA HM-5ES. For an industrial effluent to be discharged on land for irrigation purposes, its TDS should be less than 2.1 g/l and its pH should be between 5.5 - 9.0 according to the National Environmental Act (1990). The Act also states that the biochemical oxygen demand, BOD, should be less than 30 mg/l and the chemical oxygen demand, COD, should be less than 250 mg/l if the effluent is to be discharged either onto land or into water bodies. For the Embilipitiya black liquor, BOD is about 3000 mg/l and COD is about 60,000 mg/l (CISIR 1994) which are about a 100 times more than the allowable limits. An almost continuous release of black liquor of the above mentioned characteristics into a water body, as it is in the case of Embilipitiya black liquor, has the potential to kill all life-forms in the water body and eventually turn it into a dead one (Shanthini & Arulanantham 1995). Thus, black liquor is too hazardous an effluent to be let into the environment without treatment. This paper discusses briefly the treatment methods available and proposes a new type of an electrodialyzer unit in order to treat the Embilipitiya black liquor before it is discharged into the environment.

2.0 Available Treatment Methods

Black liquor from soda-pulp mills, where wood is the raw-material for paper, is successfully treated to recover energy and sodium hydroxide in a process known as the conventional chemical recovery process (Basu 1968; Panda 1991; Sinha 1970). Non-wood based black liquor, as in the Sri Lankan case where straw is

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used in place of wood, has a relatively high content of silica (Tandon et al. 1989) that causes problems such as formation of hard silica scale on the walls of the chemical recovery units (Misra 1967/68). Consequently, the number of shutdowns of the recovery unit increases and the costs of maintenance and replacement increase. (El Ebiary 1983; Panda 1989; Veeramani 1977). Nevertheless, a chemical recovery plant, that was claimed to be modified to treat the straw-based black liquor, was installed by the Germans at the Embilipitiya mills. Trials were carried on till 1983 and the silica in rice straw did cause such a number of problems that the straw-based black liquor was not even once properly treated in the chemical recovery plant of the Embilipitiya mills (Wanigasundera 1995). Even when wood-based black liquor was used in this chemical recovery plant, the black liquor had burnt itself out up to 70%, and evaporated into the atmosphere with no chemical recovery (Wanigasundera 1995). Thus, neither the straw-based black liquor nor the wood-based black liquor can be treated in the recovery plant of the Embilipitiya mills (Sofalas nee Arulanantham 1998).

Non-wood based black liquor can be treated in the conventional chemical recovery unit provided the silica is removed from black liquor prior to treating it (Govindan & Radhakrishnan 1989; Tandon et al. 1989). Excess silica can in theory be removed by lime treatment but was found unsuccessful in practice owing to many operational problems and economical concerns (Bleier 1989). Desilication by pH reduction through controlled carbonation is another possibility and pilot plant units were installed in Egypt, Indonesia and China (El Ebiary 1983; Leguen 1987; Marcks & Schildhauer 1986). Most of these units were later shut down mainly due to excessive foaming during desilication (Panda 1991; Yong 1993). Central Pulp and Paper Research Institute of India has developed a different type of reactor for desilication by controlled carbonation (Kulkarni et al. 1989) and a pilot plant unit has been installed in India (Govindan & Radhakrishnan 1989) where again foaming is reported to be causing problems (Francis et al. 1989).

Recovery of chemicals from black liquor by fractionating electrolytes from nonelectrolytes of the black liquor by the process of electrodialysis has been reported to have tremendous industrial potential almost three decades ago (Basu 1968). Electrodialysis is a simple process in which electrolytes are transferred through membranes by an electrical driving force (Rousseau 1987) and is extensively used in the production of drinking water by the desalination of seawater (Spiegler 1966). Electrodialysis, in contrast to desilication followed by an extensive chemical recovery process, appears to be a suitable one step method to recover chemicals from black liquor. Spent sulfite liquor, for instance, has been successfully separated into pulping chemicals and lignosulphonic acids in pilot plant electrodialyzer units (Basu 1968; Mishra & Bhattacharya 1984). Investigations on the influence of operating parameters on the performance of a three-compartment electrodialyzer unit have been carried out with soda-pulped straw-based black liquor by Joshi & Basu (1973) and Mishra & Bhattacharya (1984). Both these works used cellophane membranes as well as cation-exchange membranes to recover sodium hydroxide from black liquor. We have been experimenting into electrodialysis of the Embilipitiya black liquor since 1992. The progress of this research have been reported at the Faculty Research Seminars held in 1994 and in 1995 at the Faculty of Engineering of University of Peradeniya and also in the Annual Research Sessions 1996 held in the University of Peradeniya. This paper is a complete account of the results obtained so far on the electrodialysis of the Embilipitiya black liquor using a modified electrodialyzer unit proposed by us.

3.0 Experimental Setup

A three compartment electrodialyzer unit similar to the one used by Mishra and Bhattacharya (1984) was constructed with perspex and is shown in figure 1. This unit has a rectangular base of 38.9cm x 7.2cm and a height of 9.0 cm. The compartments were separated from each other by cellophane sheets. We used cellophane since it is the only membrane that is readily available in the Sri Lankan market and it is inexpensive. Black liquor used in the experiments was obtained from the Embilipitiya pulp mill and 900 ml of it was filled in the middle compartment. The outer compartments were each filled with 450 ml of distilled water. Two stainless steel electrodes, one per compartment, were placed in the two outer compartments. The electrodes were connected to a d.c. power supply unit such that one electrode acted as anode and the other as cathode. During the experiment, current was maintained constant by manually varying the voltage as described in the next section along with the results of the experiments.

During electrodialysis cations in black liquor, that are mainly sodium ions, moved through the membrane to the cathode compartment and sodium hydroxide was formed there. All the anions in black liquor moved towards the anode and of which the anions of organic acids passed through the membrane to the anode compartment where organic acids were formed. The anions of sodium lignate were held by the membrane because of the colloidal nature of lignate macromolecules which could not penetrate through the pores of

the cellophane membranes. Consequently, a lignin layer started to build up on the anode-side membrane.

The lignin layer formed on the anode-side cellophane membrane increased the cell resistance which in turn resulted in considerable increase in voltage required to maintain the constant current. Lignin deposition also caused damage to the anode-side membrane. In addition, bubbling of the liquor in the anode compartment due to rise in temperature and pitting of anode electrode were observed. These were problems that were encountered also by Mishra & Bhattacharya (1984). They reported that use of ion-exchange membranes in place of cellophane membranes improved the performance of the unit. We nevertheless decided to retain the inexpensive and locally available cellophane membrane in our experiments, but to modify the electrodialyzer unit to improve its performance.

The modified electrodialyzer unit is shown in figure 2. The stainless steel electrodes placed in the two outer compartments containing 450 ml of distilled water each were turned into cathodes. An open box of 11.6cm x 5.5cm rectangular cross-section was constructed with a perspex bottom and four cellophane side walls of 5.0 cm height reinforced by a perspex grid. This box was filled with 400 ml of distilled water and a third stainless electrode was placed inside it.

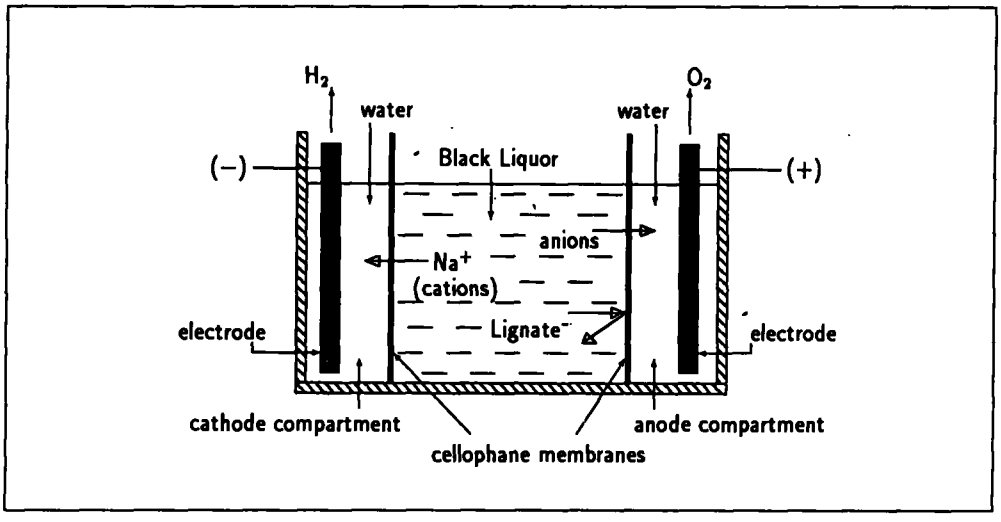

Figure 1 - A three compartment electrodialyzer unit similar to the one used by Mishra and Bhattacharya (1984).

This third electrode was the anode. The whole set up was placed in the middle of the compartment holding 600 ml of black liquor. Placed in the black liquor was another open box of 17.3cm x 5.9cm rectangular cross-section and 9.0 cm height made entirely of plastic mesh which surrounded the small anode compartment on all four sides and at the bottom.

During electrodialysis, sodium ions in black liquor moved towards the cathode electrodes and sodium

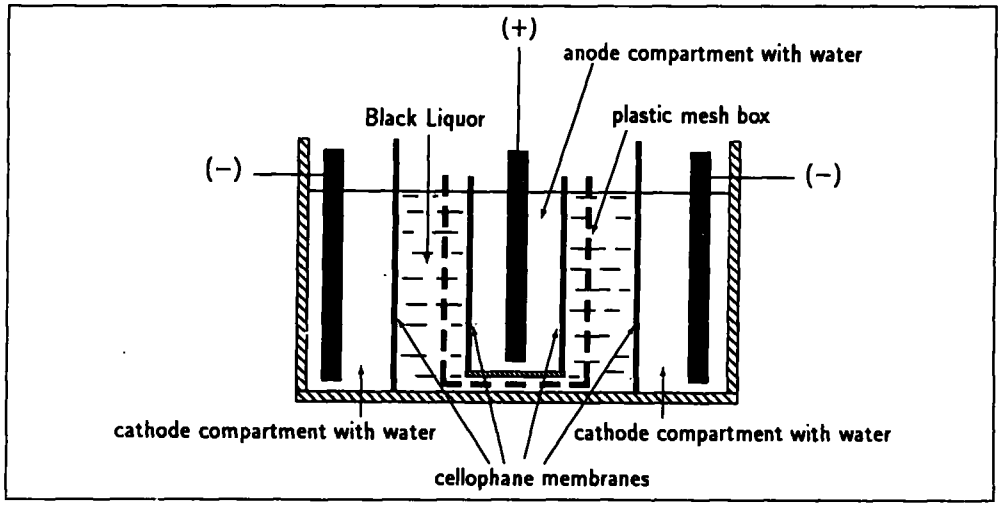

Figure 2 - Modified electrodialyzer unit used in this study.

hydroxide solutions were formed in both the cathode compartments. Anions of organic acids moved towards the anode and organic acids were formed in the anode compartment. Lignin did not deposit on the anode-side membrane, but was collected on the bottom of the mesh box. Because of the deposit-free anode-side membrane, the process of electrodialysis was continued until the black liquor in the middle compartment lost almost all its ions to cathode and anode compartments. Motion of the ions in the unit was monitored by periodically measuring the electrolytic conductivity of the solutions in the anode, cathode and black liquor compartments.

Determination of electrolytic conductivity is performed by measuring the resistance occurring in an area of the test solution defined by the design of the probe of conductivity meter Hach 44600. The conductivity probe is not ion-selective and It measures the sum total of the concentrations of inorganic components of the solution. Temperature of the solution is measured by a thermistor network in the conductivity probe. Conductivity measurements are compensated by a coefficient of 2% per degree Centigrade to provide a reading equivalent to what it would be at the reference temperature 25 degree C.

4.0 Experimental Results and Discussion

Figure 3 shows the experimental results obtained up to 3 hours of electrodialysis with fresh, straw-based black liquor obtained from the lab-scale digester of the Embilipitiya pulp mills. Circles (o) represent the temporal development of the conductivity of the NaOH solution in the cathode compartment of Mishra & Bhattacharya type unit shown in figure 1. Pluses (+) represent the temporal development of the average conductivity of the NaOH solutions in the two cathode compartments of the modified unit shown in figure 2. Both results were obtained maintaining 500 mA current throughout the electrodialysis with stainless steel electrodes of 11.4 mm diameter.

It can be seen in figure 3 that the total inorganic ion concentration in the cathode compartment is higher in the modified unit than in the unit duplicating the one used by Mishra & Bhattacharya for the same current of 500 mA. This observation can be attributed to the double-cathode setup of the modified unit as opposed to the single-cathode setup of the old type unit. The modified unit can practically be described as two electrodialyzer units in series with one anode compartment in common. Whereas, the Mishra & Bhattacharya type unit is just one single electrodialyzer unit.

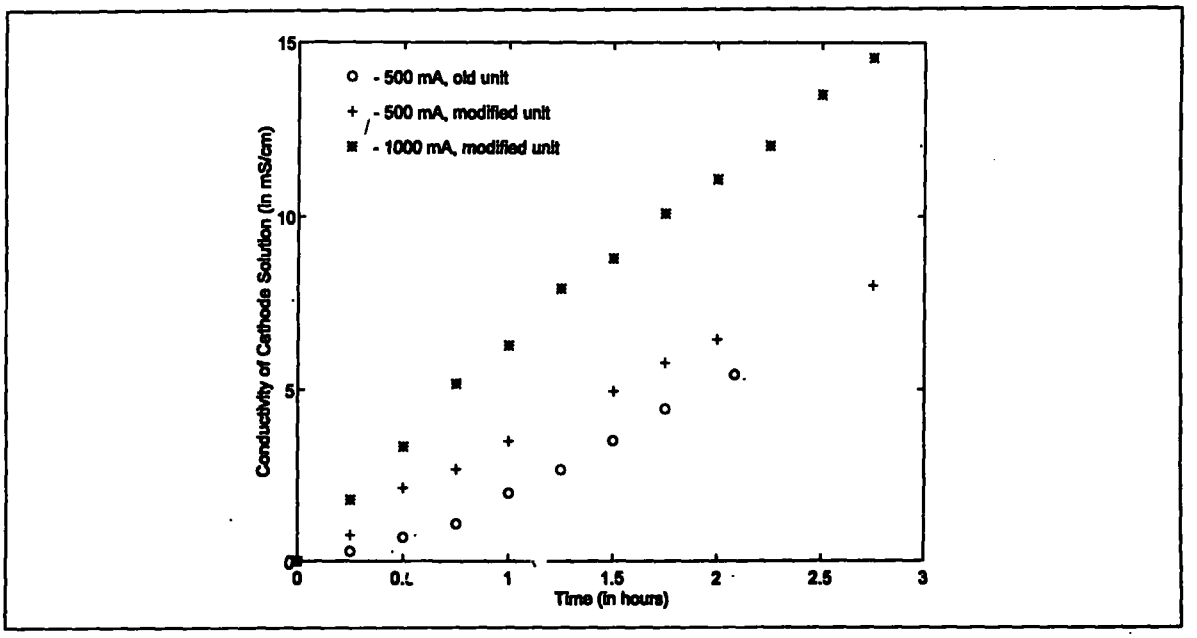

Figure 3 - Temporal development of cathode solution conductivity during electrodialysis of Embilipitiya fresh, straw-based black liquor in two different types of units.

Electrodialysis was possible only for about 2 hours in the old type unit because of the increasing cell resistance owing to the lignin layer forming on the anode-side cellophane membrane. Whilst, electrodialysis in the modified unit was carried out for three hours and could have been carried out for more than three hours, if required. It was because most of the lignate ions moving towards the anode electrode of the modified unit did not form a lignin layer on the cellophane walls of the anode compartment but were collected on the bottom of the plastic mesh box.

Asterisks (*) of figure 3 represent the results obtained with the modified unit at 1000 mA current using stainless steel electrodes of 31.4 mm diameter. It is of considerable importance to note that the modified unit allowed currents as high as one Ampere owing to lignin-free cellophane as anode walls whereas such high current was not at all possible in the old setup with cellophane membranes. Higher current indeed resulted in higher ion concentrations in cathode compartment which meant better ion-removal from black liquor.

Presence of plastic mesh walls near the anode compartment walls is a factor that solely contributed towards the advantageous phenomenon of lignin-free cellophane as anode walls which in turn considerably improved the performance of the electrodialyzer unit. The mesh seemed to offer physical resistance to the colloidal macromolecular lignate ions moving towards the anode walls and consequently provided a site for the lignate ions to settle on. The lignate ions turned to lignin solids by accepting the hydrogen ions that seeped out of the anode chamber.

Figure 4 shows results that were obtained with stainless steel sheets of 43.5mm x 2mm cross-section as electrodes with plastic mesh outer box (represented by circles) and with metal wire mesh outer box (represented by crosses). A current value of 1000 mA was maintained initially. Because of the decreasing electrolytic conductivity of black liquor with time, it became increasingly difficult to maintain 1000 mA current. After about 10 hours of electrodialysis, the unit was to be run at the maximum voltage of 140 V which meant the current passed was only about 100 mA. As can be seen from figure 4, the results obtained with the metal wire mesh outer box differ only slightly from the results obtained with the plastic mesh outer box. However, corrosion limited the life span of the metal wire mesh to about 20 hours of electrodialysis only.

The circles of figure 4 fit in three distinctly different curves labeled OA, BC and CD. These three curves represent three different runs that were carried out one after the other with one single batch of black liquor. Each of the three runs was however started with fresh distilled water in anode and cathode chambers. Curve OA of figure 4 spanning from 0 to 6.67 hours represents the first run during which the conductivity of black liquor decreased from 19 mS/cm to 13 mS/cm and the average conductivity of cathode solutions increased from 0 to about 27 mS/cm. At the beginning of the run, the flow of sodium ions from black liquor chamber to cathode chambers was caused by the favorable concentration gradient as well as the electric potential gradient. Towards the end of the run, however, the concentration gradient became adverse and hence the flow of sodium ions from black liquor chamber to cathode chambers slowed down as shown by the decreasing gradient of curve OA.

At the end of the first run, the cathode solutions of 27 mS/cm conductivity were removed and the cathode chambers were once again filled with 450 ml of fresh distilled water each. As can be seen from the gradient of the second curve of circles BC, the flow of ions from

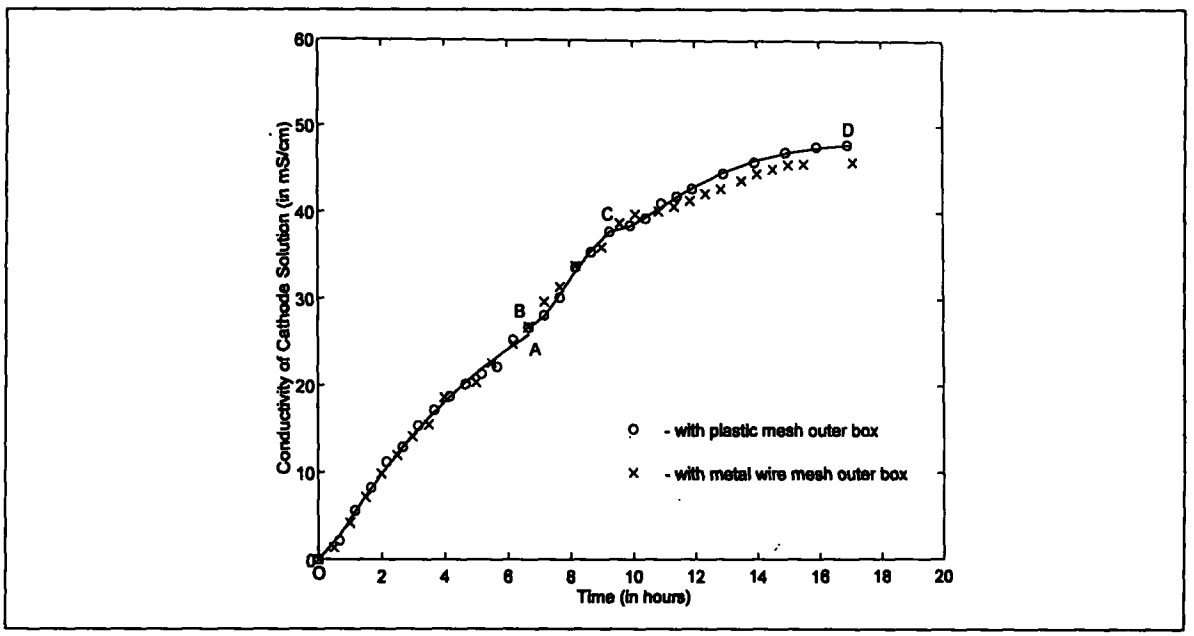

Figure 4 - Cumulative conductivity of cathode solution during electrodialysis of fresh, straw- based black liquor in the modified unit with two different mesh outer boxes.

black liquor chamber to cathode chambers immediately improved owing to the favorable concentration gradient experienced by the sodium ions in addition to the electric potential. The curve BC spanning from 6.67 to 9.25 hours represents the second run during which the conductivity of black liquor decreased from 13 to 7 mS/cm and the average conductivity of cathode solutions increased from 0 to about 11 mS/cm. The curve CD spanning from 9.25 to 17 hours represents the third run during which the conductivity of black liquor decreased from 7 to 0.4 mS/cm and the average conductivity of cathode solutions increased from 0 to about 10 mS/cm.

The respective average conductivity of the cathode solutions obtained at the end of each of the three runs with the plastic mesh were about 27, 11 and 10 mS/cm. These values are equivalent to that of 0.14N, 0.06N and 0.05N NaOH solutions, respectively, according to the linear relationship,

$$\text{Normality of NaOH solution} = \frac{(\text{conductivity in mS/cm} - 0.63)}{/\ 183.5,}$$

which was obtained by calibrating the conductivity readings against NaOH solutions of known concentrations. Figure 4 also shows that at the end of 17-hour electrodialysis, the cumulative value of the average conductivity of the cathode solutions went up to about 45 mS/cm. To obtain a NaOH solution of 0.24N at the end of 17 hours of electrodialysis, however, all the resulting cathode solutions must be added together and the volume be reduced to the original 900 ml by evaporation. Purity of the sodium hydroxide solutions collected in the cathode compartments has not yet been analyzed owing to lack of adequate funds.

The results obtained with the wiremesh outer box exhibit features that are very similar to those observed with the plastic mesh outer box as can be seen figure 4. At the end of the 17-hour electrodialysis, the cumulative conductivity of the cathode solutions changes only marginally with time in both the cases represented by circles and crosses. This feature of figure 4 signals the end of electrodialysis for the batch of black liquor processed. Conductivity of black liquor at this state was about 0.4 mS/cm. At conductivity as low as 0.4 mS/cm, almost all the sodium ions in black liquor had been lost to the cathode compartments. And, the original black liquor in the middle compartment was observed to have become a light brown liquor with suspended and settled solids. When these dark coloured solids, mostly lignin, were removed from the liquor by filtration, an almost colourless liquor was obtained as the filtrate. Thereby, the black colour of the black liquor has been successfully removed by the process of electrodialysis carried out in the unit proposed in this study.

The pH of the original black liquor was 10 and the pH of the filtrate was 6 which falls within the acceptable pH-range of 5.5 - 9.0 for a liquid effluent to be discharged onto the environment as per the environmental standards of Sri Lanka (National Environmental Act 1990). The original black liquor had a TDS of about 64 g/l and the TDS of the colourless filtered liquor was only 0.2 g/l which is much less than the stipulated limit 2.1 g/l of TDS for an industrial effluent to be discharged on land for irrigation purpose as per the environmental standards for Sri Lanka (National Environmental Act 1990). To release the filtered liquor to an inland surface water body, the TDS has to be further reduced to 0.05 g/l (National Environmental Act 1990). Low TDS values may be achieved by subjecting the filtrate to conventional biological waste treatment processes since the filtrate is free of the macromolecular lignate ions that offer high resistance to biodegradation. Research is underway to optimize the final TDS value of black liquor at which electrodialysis could be halted to give way to efficient biodegradation.

The major drawback of the electrodialyzer unit was that the anode liquor, comprising mainly of organic acids, offered high resistance to the flow of electricity. For example, at the end of the 17-hour electrodialysis, electrolytic conductivity in the anode chamber went only up to 2 mS/cm indicating the comparatively high resistance prevailing in the anode chamber. Such high resistance in the anode chamber led to comparatively large energy dissipation in the anode chamber which in turn increased the temperature of the anode liquor as high as 80 degree C. Such high temperatures resulted in bubbling and evaporation losses of anode liquor as well as leaks at the joints of the perspex unit. All these adverse features were avoided when the temperature of the anode liquor was maintained below 65 degree C. A series of runs were carried out with anode liquor at 60 degree C by circulating the anode liquor through a water-cooler by use of a pump.

Figure 5 shows the results obtained in the modified unit with and without cooling. Both the results shown were obtained with stainless steel sheets as electrodes and with 1000 mA initial current. After about 10 hours of electrodialysis, the unit was to be operated at the maximum voltage of 140 V which permitted only about 100 mA current in both cases of with and without cooling. It can be observed in figure 5 that the overall recovery of sodium ions with cooling is better than the recovery obtained without cooling. The initial rate of recovery of sodium ions, however, exhibits an entirely opposite feature. Maintaining the temperature of the anode liquor temperature at 60 de-

gree C or below, most importantly, saved the unit from developing leaks. Besides, bubbling of anode liquor and evaporation losses of anode liquor are all completely eliminated.

Temperature of anode liquor can be maintained constant not only by cooling the anode liquor but also by manipulating the voltage applied which is best done by interfacing the electrodialyzer unit to a computer for data acquisition and control. The modified electrodialyzer unit has at present been automated to aid not only a thorough investigation into the influence of anode liquor temperature on the overall performance of the modified electrodialyzer unit but also to facilitate means for a thorough parametric study of the modified electrodialyzer unit.

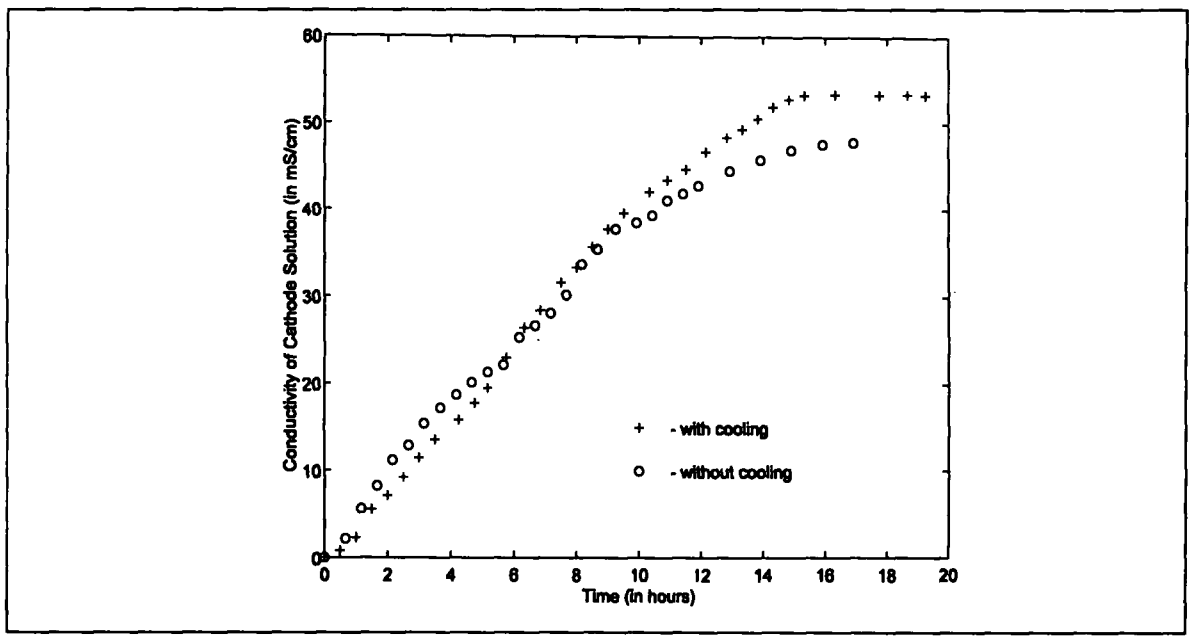

Figure 5 - Cumulative conductivity of cathode solution during electrodialysis of fresh, straw-based black liquor in the modified unit with and without cooling of anode liquor.

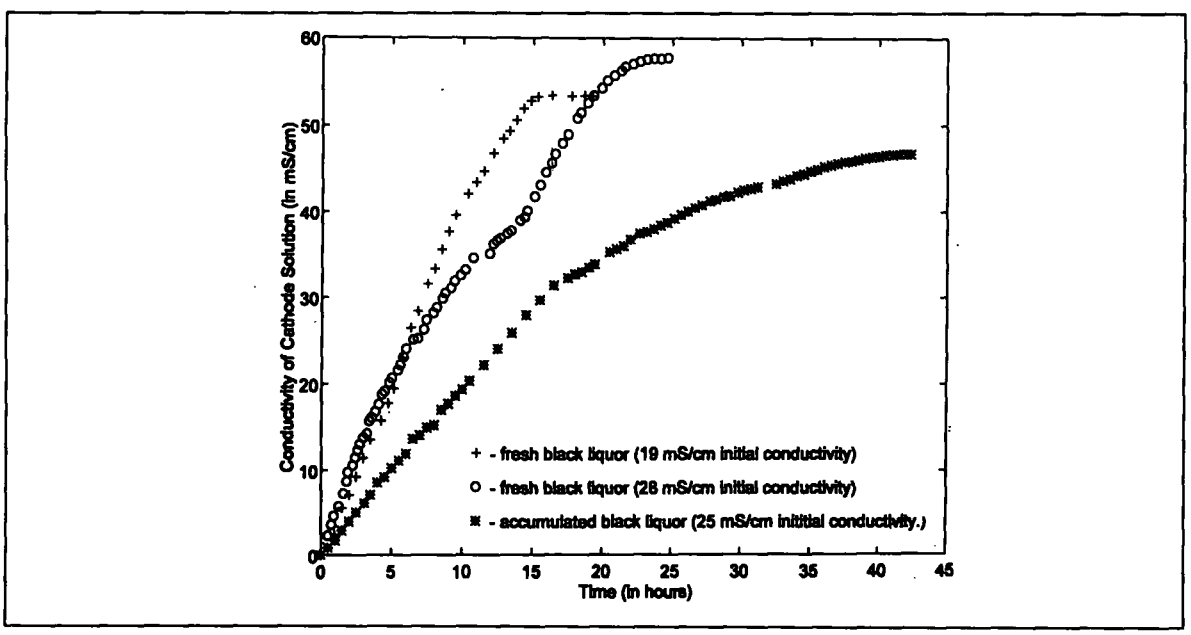

Figure 6 - Cumulative conductivity of cathode solution during electrodialysis of fresh and accumulated black liquors from the Embilipitiya pulp mill.

Figure 6 shows the results obtained in the modified unit with different types of black liquors from the Embilipitiya mills. Plus signs (+) of figure 6 represent the same results as by the plus signs of figure 5 which were obtained during electrodialysis of fresh, straw-based black liquor with cooling so as to maintain the temperature of anode liquor at 60 degree C. Circles (o) of figure 6 represent the results obtained during electrodialysis of wood-based black liquor maintaining the anode liquor temperature at an average value of 60 degree C by varying the current through out electrodialysis. The former had an initial conductivity of 19 mS/cm and yielded a cathode solution of 53 mS/cm of cumulative conductivity which was equivalent to a 0.29N NaOH solution. The latter had an initial conductivity of 28 mS/cm and yielded a cathode solution of 58 mS/cm of cumulative conductivity which was equivalent to a 0.31N NaOH solution. These results are of course consistent with the fact that the amount of NaOH required for pulping of wood is more than what is required for pulping of straw since the lignin content of wood is higher than that of straw (Tandon et al. 1989).

The circles of figure 6 can be observed to fit in two very different curves: the first curve of circles represents one continuous run at the end of which, the average conductivity of cathode solutions was at about 40 mS/cm, which is equivalent to the conductivity of a 0.2N NaOH solution. At this state, the conductivity of black liquor was 15 mS/cm. The adverse concentration gradient of the sodium ions considerably slowed down the flow of sodium ions from black liquor chamber to cathode chambers that was caused by electric potential gradient. At the end of the first run, the cathode solutions of 40 mS/cm conductivity were replaced by 450 ml of distilled water each. As can be very clearly seen from the second curve of circles, the flow of ions from black liquor chamber to cathode chambers immediately improved owing to the favorable concentration gradient experienced by the sodium ions in addition to the electric potential.

The curve of pluses appears a continuous one because the cathode solutions were replaced at appropriate times. The first change was 6.3 hours after the start of electrodialysis at which time, the average conductivity of cathode solutions was about 26 mS/cm and the second change was about another 6.5 hours after at which time the average conductivity of cathode solutions was about 22 mS/cm. The above results show that replenishing the cathode liquors with distilled water at optimum time intervals remarkably improve the performance of the electrodialyzer for obvious reasons. Investigations are underway for finding a suitable criterion that would predict the best time for replacing the cathode solutions with distilled water in processing a batch of black liquor. Anode liquor requires no replenishment during batch processing.

The asterisks (*) of figure 6 were results obtained during electrodialysis of accumulated black liquor from Embilipitiya. The accumulated black liquor has been stored in large stabilization ponds covering a land area of about 35 acres in the vicinity of the pulp mill before being discharged into the Walawe river. This land space for storing black liquor should of course increase as and when the pulp mill produces black liquor provided there is no continuous release of black liquor into the Walawe river even though evaporation accounts for some loss of accumulated black liquor volume. To obtain the end results similar to that of the fresh black liquors, the accumulated black liquor was fractionated in the modified electrodialyzer unit for 40 hours which was much longer than the time required for fresh black liquors even though the initial conductivity of the accumulated black liquor was in between those of the fresh black liquors. This result clearly indicates that the chemical nature of the accumulated black liquor is very different from that of the fresh liquors. The silicates and the lignates of the black liquor are known to precipitate upon storage in open ponds in a process known as the natural carbonation (Panda 1989; Kulkarni et al. 1989).

A thorough analyses of the physical and chemical properties of different types of black liquors would certainly enrich our knowledge about the liquors that we are trying to treat. It is also imperative to determine the exact chemical nature of the liquors that are products of our research work. All these analyses must be and will be carried out as soon as adequate financial support is found for this research.

5.0 Concluding Remarks

Fresh, straw-based black liquor of the Embilipitiya pulp mill is successfully fractionated into sodium hydroxide, lignin and organic acids by the process of electrodialysis in the modified lab-scale electrodialyser unit proposed in this study. One of the major environmental problems of Sri Lanka, which is the accumulated black liquor stored in large stabilization ponds at Embilipitiya mills is also successfully fractionated in the modified unit into the aforementioned chemicals.

Damage to the anode-side cellophane membrane due to lignin deposition and bubbling of liquor in the anode compartment, both are problems that limited electrodialysis of black liquor, have been completely eliminated in the unit proposed in this paper. The modified unit, even with cellophane membranes, gives NaOH solutions of strength 0.1N or more. Black liquor subjected to the process of electrodialysis fol-

lowed by filtration is changed into a colourless liquor of 6 pH and 0.2 g/l TDS. This filtered liquor is qualified to be discharged on land for irrigation purpose as per the environmental standards for Sri Lanka as far as the pH and TDS are concerned. Organic acids collected in the anode compartment of the modified unit should be subjected to extensive physical and chemical analyses to establish possible commercial uses for these acids. Lignin solids that are separated from black liquor have, apart from their high fuel value, a number of uses such as reinforcing agent for rubber, as binder in printing inks and foundry sand, as protective colloid in soap emulsions, as dispersing agent for clays, as fire foam stabilizer and as ion-exchange resins. Lignin can also be a raw material for many useful organic compounds. Recycling the sodium hydroxide solution to the pulp mill for digesting straw and the filtered liquor to the process along with discovering suitable commercial utilization of the organic acids and lignin are steps that can be taken to move the straw-based paper-making industry towards the zero-effluent status sought after by process industries of today.

Optimization of the influencing parameters and hence possible further modifications to the proposed lab-scale electrodialyzer unit are being investigated at present with the objective of considerably reducing the batch processing time. Modeling the performance of the batch-electrodialyser is also researched into in order to understand the dynamics of the electrodialysis process of black liquor. This understanding is imperative in converting the lab-scale unit of this study to a pilot-plant-scale unit. A detailed pilot-plant-scale study is a prerequisite to address important issues such as the scale-up and the economics of the electrodialysis treatment of Embilipitiya black liquor that are crucial in the eventual adaptation of the lab-scale solution of this study to the industrial application.

6.0 Acknowledgements

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