HEAT AND MOMENTUM TRANSFER PARAMETERS OF BAGASSE BLACK LIQUOR

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ABSTRACT

One of the major process streams in pulp and paper industry is black liquor. For economical and environmental reasons, chemicals and heat are recovered by burning the concentrated black liquor. Rheological and thermal properties of bagasse kraft liquor such as density, viscosity, specific heat, thermal conductivity and heat transfer coefficient were studied. Such properties for bagasse kraft black liquor are generally spare, not very precise, and either not complete, or not available. Reliable correlations for such physical properties were given covering concentration range from 2.5% to 52%, and different temperatures from 20 to 90 °C. General correlations gathering all these properties are given for laminar and turbulent conditions:

For laminar conditions: $Nu = 0.035\ Re^{0.69}\ Pr^{0.3}\ (\mu_b/\mu_w)^{0.14}$

Valid for $4 < Pr > 30$ and $L/D = 11.03$

For turbulent conditions : $Nu = 0.126\ Re^{0.52}\ Pr^{0.3}\ (m_b/m_w)^{0.14}$

Valid for $2 < Pr > 6$ and $L/D = 11.03$

Keywords: Black liquor, Therrmal analysis , Rheological analysis , Heat transfer coeficient

INTRODUCTION

The pulp mill capacity is normally limited by the capacity of recovery furnace. The first stage of any chemical engineering design is to find the physical properties of the process stream. One of the major process stream in the pulp and paper industry is black liquor. Black liquor has physical properties which vary greatly with temperature, solid contents, and its chemical composition. Several studies on the physical properties of black liquor from wood pulp have been found in the literature, [1-7]. Most of them have concentrated on measuring the viscosity of the black the liquor. The other physical properties of black liquor such as density and specific heat were also dealt with [3, 8-12]. Thorough research in literature revealed a lack of information on thermal conductivity and heat transfer coefficient of black liquor, either sulfite or sulfate woody materials and no information was given on kraft bagasse black liquor.

The overall object of this study is to determine the heat transfer parameters as well as fluid transfer parameters of kraft bagasse black liquor such as density, viscosity, specific heat, thermal conductivity and heat transfer coefficient. These parameters are studied over a wide range of liquor concentrations and a wide range of temperatures, in order to obtain reliable correlations useful for engineering design of equipments used for heat recovery and chemical recovery from kraft bagasse black liquor.

EXPERIMENTAL TECHNIQUES AND EQUIPMENT

Materials

The black liquor used in this study was an Egyptian bagasse kraft black liquor; it was provided from Edfo pulp Mill, Aswan governorate, Egypt. The black liquor was obtained in three different concentrations 8.5, 34, and 52% . The other concentrations of the black liquor test sample are prepared by appropriate dilution of the stock solutions. The chemical analysis of bagasse kraft black liquor is given in Table 1. All data are presented on a dry weight basis.

Table 1 Chemical analysis of bagasse kraft black liquor.

Particulars	Value
TDS, %, w/w	8.5
pH.	10
Organic, %, w/w	67.08
Inorganic, %, w/w	32.92
Silica and insoluble matter, %, w/w	3.31
Lignin, %	22.03
Carbohydrates, %, w/w	45.05
Residual Active Alkali (RAA) as Na_2O, g/L	4.03
Total Alkali (TA) as Na_2O, g/L	17.98
Elemental analysis:	
Total carbon, %, w/w	33.1
Total sodium, %, w/w	23.54
Total sulphur, %, w/w	4.4
Total nitrogen, % w/w	0.19
Total hydrogen, % w/w	3.4
Total oxygen, % w/w	31.4

Density and Specific Gravity Measurements

The density of bagasse kraft black liquor at different concentrations up to 40% (TDS) and different temperatures from 20 to 98 °C was obtained using density bottles.

Viscosity Measurement

The viscosity of bagasse kraft black liquor of different concentrations up to 52% (TDS) and different temperatures from 20 to 85 °C was measured. A capillary viscometer (Ostwald) and a constant temperature bath (± 0.1°C) was used for samples up to 20% concentration. Rotational viscometer (Rheotest 2.1) was used for the range of 20 to 52% concentration black liquor.

Specific Heat Measurement

Specific heat of bagasse kraft black liquor at different concentrations up to 52% (TDS) and different temperatures up to 93 °C was measured using the Williams method.

Thermal Conductivity Measurement

Most of the methods permitting the evaluation of the thermal conductivity of materials are based on steady state conditions. Thermal conductivity of bagasse kraft black liquor at different concentrations up to 40% (TDS) and different temperatures up to 95 °C was determined using the tube method, [13]

Heat Transfer Coefficient Measurement

Measurement of heat transfer coefficient for bagasse kraft black liquor under different operating conditions was made using an ARMFIELD concentric tube heat exchanger supplied by. The unit consists of concentric tube exchanger in the form of a **"U"**. The external surface of the exchanger is insulated. Three temperature measuring devices are installed on the inside and the outside. To minimize losses in the system, the hot fluid is fed through the inner pipe, with cooling water in the outer annulus. The flow rates are measured using independent flowmeters installed in each line. A hot storage tank is equipped with an immersion type heater and an adjustable temperature controller, which can maintain the temperature to within approximately ± 0.1°C. Circulation to the heat exchanger is provided by a pump, and fluid returns to the storage tank via baffle arrangement to ensure adequate mixing. The water fluid required for the exchanger is taken from the laboratory mains supply.

Calculation of Heat Transfer Coefficient

For counter current flow, the following four terminal temperatures are taken at steady state:

- temperature of entering hot fluid and leaving hot fluid, T_{hi} and T_{ho} respectively;
- temperature of entering cold fluid and leaving cold fluid, T_{ci} and T_{co} respectively.

The approach is:

$$\Delta T1 = (T_{hi} - T_{co}) \quad ; \quad \Delta T2 = (T_{ho} - T_{ci})$$

Logarithmic mean temperature difference

$$\Delta T_{lm} = \frac{\Delta T1 - \Delta T2}{\ln \dfrac{\Delta T1}{\Delta T2}}$$

The heat flow rate through the wall of the concentric tube was calculated from the following equation,

$$q = UA_{ave.} \Delta T_{lm.} \quad (1)$$

where:

$$UA_{ave.} = \frac{1}{\frac{1}{h_i A_i} + \frac{\ln(r_o/r_i)}{2\pi lk} + \frac{1}{h_o A_o}} \quad (2)$$

and q is also equal to the rate of heat emitted from the hot fluid, $q = mCp_{ave.}(T_{hi} - T_{ho})$, which can be written as :

$$q = V \rho_{ave.} Cp_{aver.} (T_{hi} - T_{ho}) \quad (3)$$

where V is the liquor flow rate and ρ_{ave} and $Cp_{ave.}$ are the average density and average heat capacity respectively of the liquor at the bulk mean steady state liquor temperatures. The heat transfer coefficient of hot fluid (h_i) is calculated by means of Equations 1, 2 and 3 .

RESULTS AND DISCUSSION

Density

Densities of kraft bagasse black liquor for a range of solid content from 2.4 to 40% (water, 0% solid content, included) and for a temperatures from 20 to 98°C, are shown in Figure 1. As expected the density was found to increase with solid content and decrease with temperature. The measured data could be correlated in the form,

$$\rho = \rho_{water} [1 + (TDS/100)(0.475 + 0.00166T)] \quad (4)$$

The agreement between measured and predicted values (Equation 4) is satisfactory as shown in Figure 2. The deviation was ±2% over the ranges of concentrations and temperatures studied. Compared to the work of Branch and Muller [12], on wood kraft black liquor, a small difference was found, as shown in Figure 1, due to differences in the black liquor constituents. This difference results from difference in concentration of pulping liquor, pulping conditions and raw material; Branch and Muller used pine kraft black liquor [12].

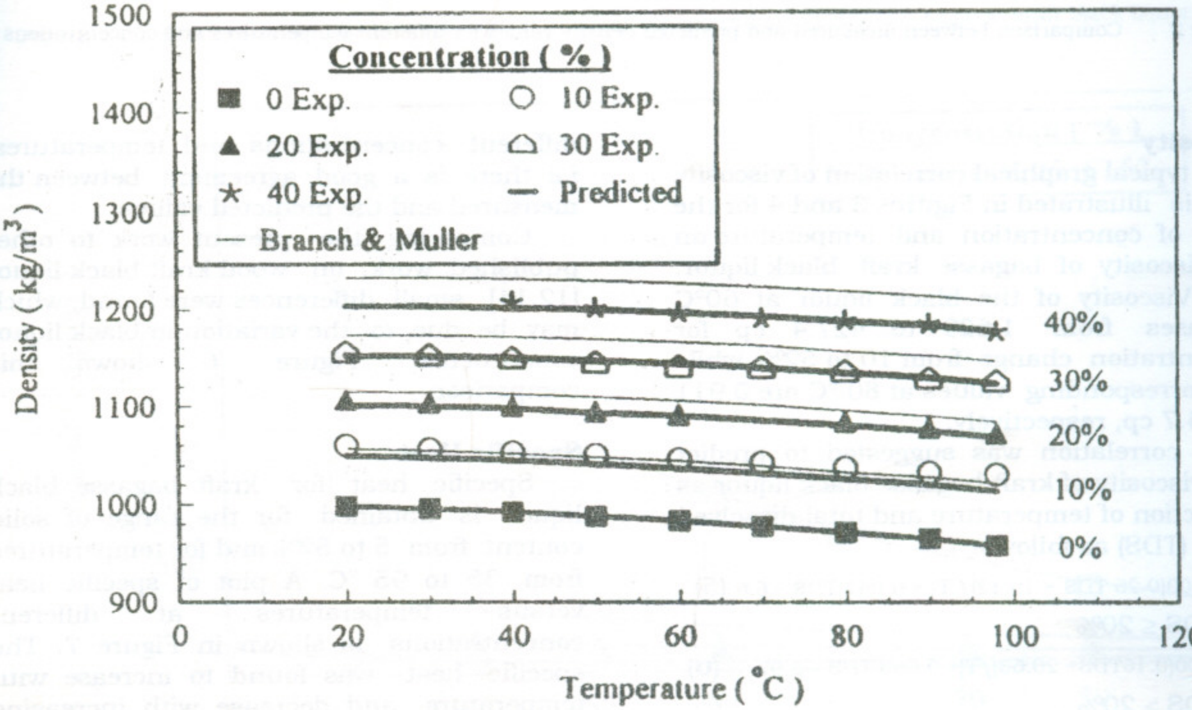

Figure 1 Comparison between experimental, predicted and Branch Muller density values for bagasse kraft black liquor at different temperatures and concentrations

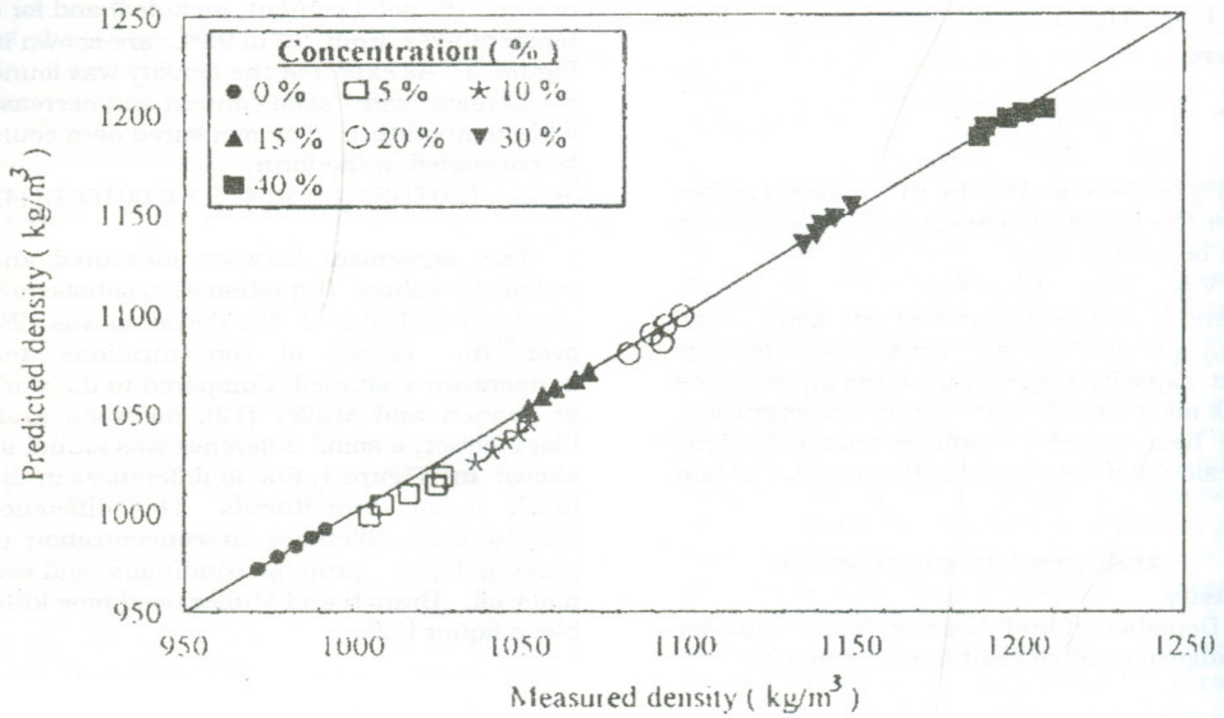

Figure 2 Comparison between measured and predicted density values for different temperatures and concentrations

Viscosity

A typical graphical correlation of viscosity data is illustrated in Figures 3 and 4 for the effect of concentration and temperature on the viscosity of bagasse kraft black liquor. The Viscosity of the black liquor at 60°C increases from 1.629 to 427.4 cp for concentration change from 10 to 52%, while the corresponding values at 80 °C are 0.911 to 274.7 cp, respectively.

A correlation was suggested to predict the viscosity of kraft bagasse black liquor as a function of temperature and total dissolved solids (TDS) as follows:

$$\ln \mu = [100(0.26\ TDS + 19.12)/\ T] + 0.047\ TDS - 6.6 \quad (5)$$

for $TDS \leq 20\%$

$$\ln \mu = [100(0.16TDS + 20.63)/T] + 0.063\ TDS - 5.92 \quad (6)$$

for $TDS > 20\%$

A comparison between measured and predicted viscosity values (Equations 5 and 6) is shown in Figure 5. All values approximately fall on the 45° line for different concentrations and temperatures; i.e there is a good agreement between the measured and the predicted values.

Comparing the present work to other published work, on wood kraft black liquor [12,14], small differences were found, which may be due to the variation in black liquor constituents. Figure 6 shows this comparison

Specific Heat

Specific heat for kraft bagasse black liquor is obtained for the range of solid content from 5 to 52% and for temperatures from 35 to 95 °C. A plot of specific heat versus temperatures at different concentrations is shown in Figure 7. The specific heat was found to increase with temperature and decrease with increasing solids content. This is entirely consistent with the nature of all the organic and inorganic constituent of the wood black liquor,[12, 15].

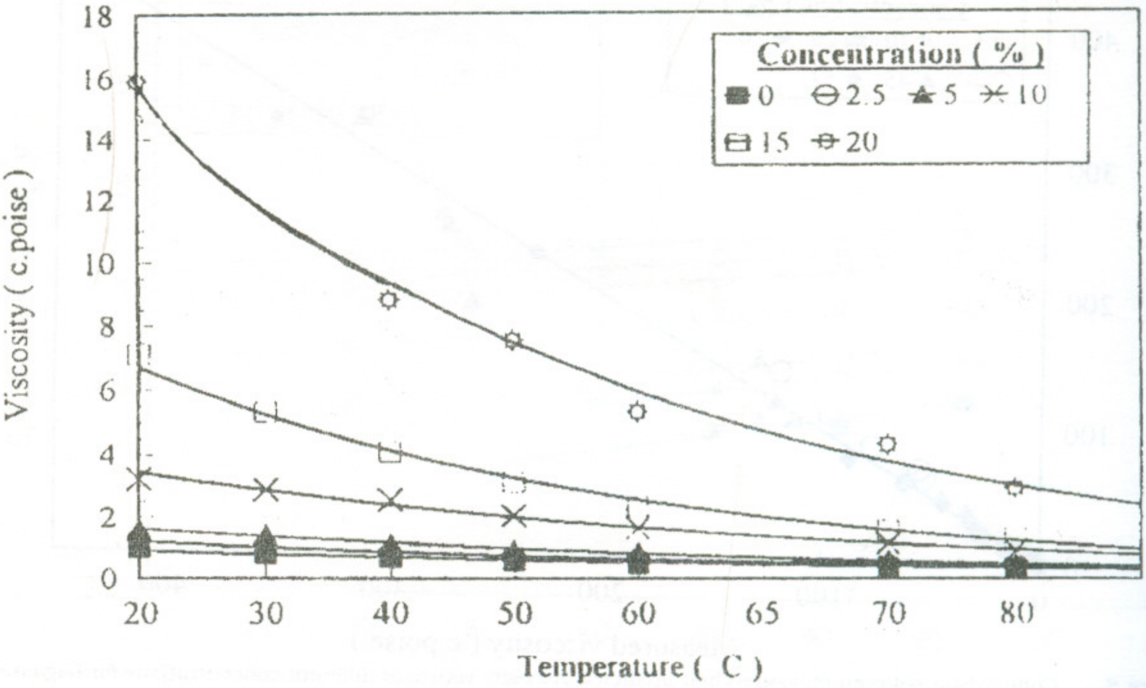

Figure 3 Effect of temperature on viscosity at different concentrations (0:20%) for bagasse kraft black liquor

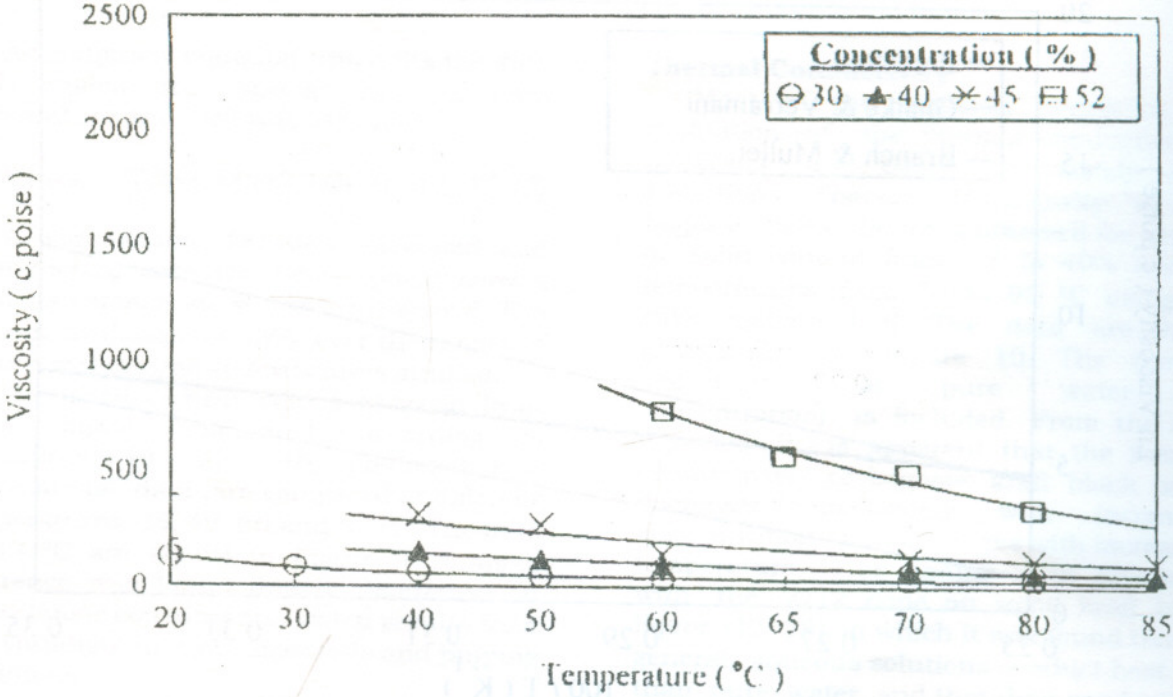

Figure 4 Effect of temperature on viscosity at different concentrations (30:52%) for bagasse kraft black liquor

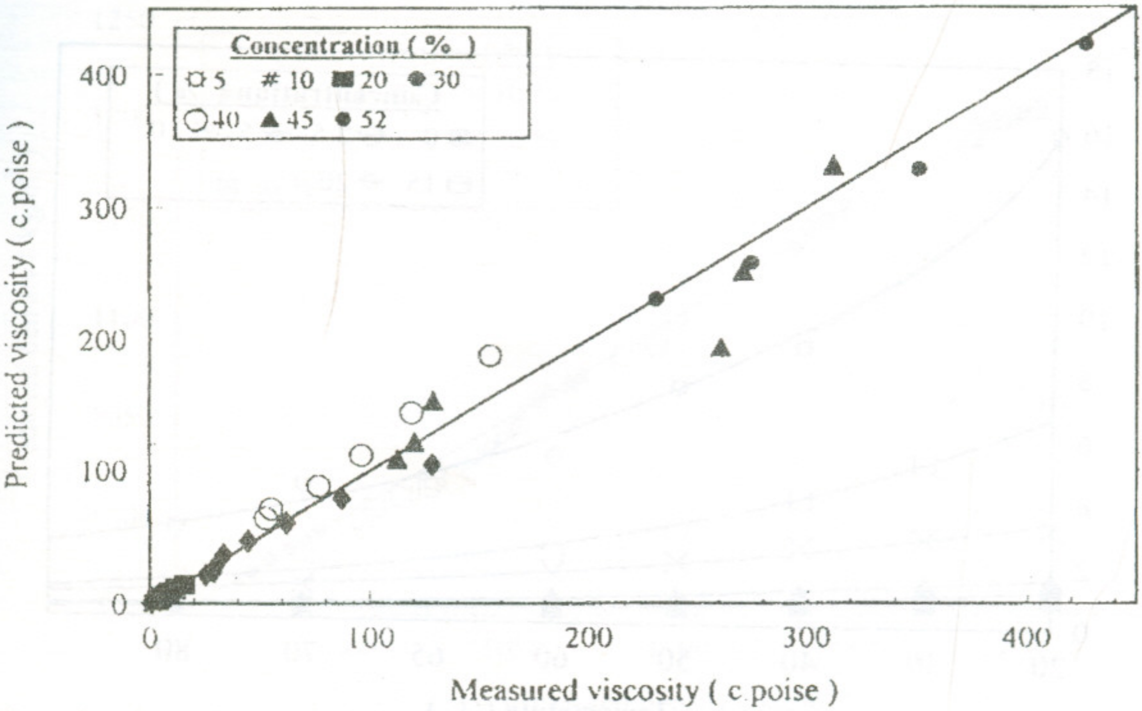

Figure 5 Comparison between measured and predicted viscosity values at different concentrations for bagasse kraft black liquor

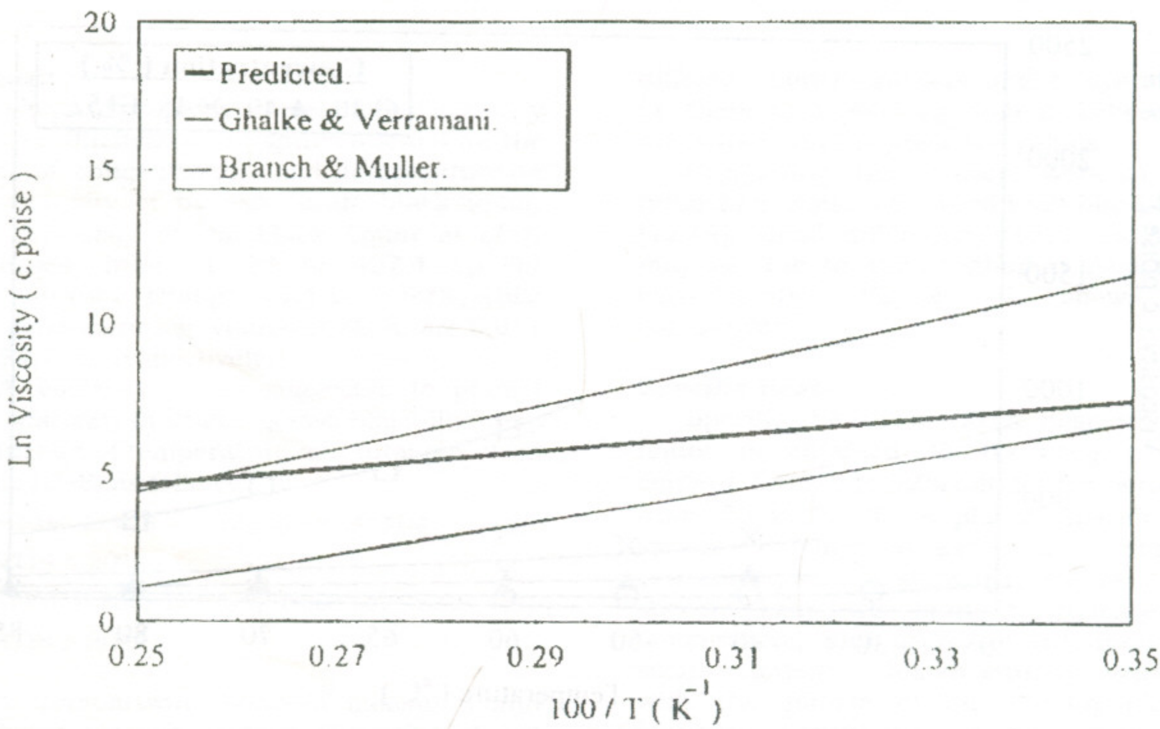

Figure 6 Comparison between predicted, Branch and Muller and Chalke [12] and Verramani [14], viscosity data for bagasse kraft black liquor at 52% concentration

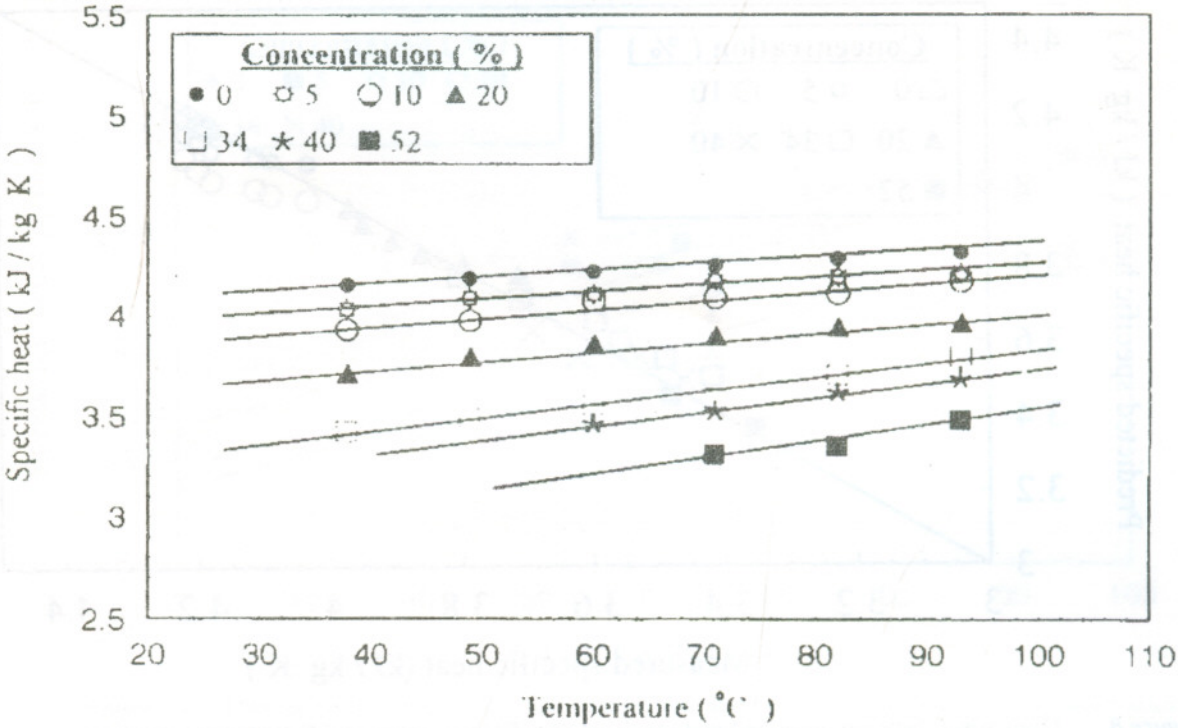

Figure 7 Comparison between measured and predicted specific heat values at different concentrations

An empirical equation which fits the data and relates the specific heat to both temperature and TDS was obtained:

$$Cp = Cp_{water} - (TDS/100)(2.445 - 0.01213T) \quad (7)$$

A comparison between correlated and experimental data for heat capacity show a good agreement as shown in Figure 8. The present deviation is ±3% over the ranges of concentrations and temperatures studied.

The specific heat values of wood kraft black liquor calculated according to References 12 and 16, predicted and experimental data are compared at different temperatures 38, 49, 60 and 82 °C. The data at 49 °C are shown in Figure 9. A small difference was found due to differences in black liquor constituents, which results from the variation in raw materials and pulping conditions.

Thermal Conductivity

Most of the methods permitting the evaluation of the thermal conductivity of materials are based on steady state conditions. Thermal conductivity of kraft bagasse black liquor is obtained for a range of solid content from 2.5 to 40% and for temperatures from 33 to 95 °C using the tube method [13]. The data are shown graphically in Figure 10. The thermal conductivity of pure water (0% concentration) is included. From the data obtained it is apparent that the thermal conductivity of bagasse kraft black liquor decreases moderately with increasing concentration and increases with increasing temperature. This finding is in agreement with the work done on wood kraft black liquor [17, 18], in which it was found that, in general, aqueous solutions conduct heat less than pure water and that their conductivity decreases with increasing concentrations.

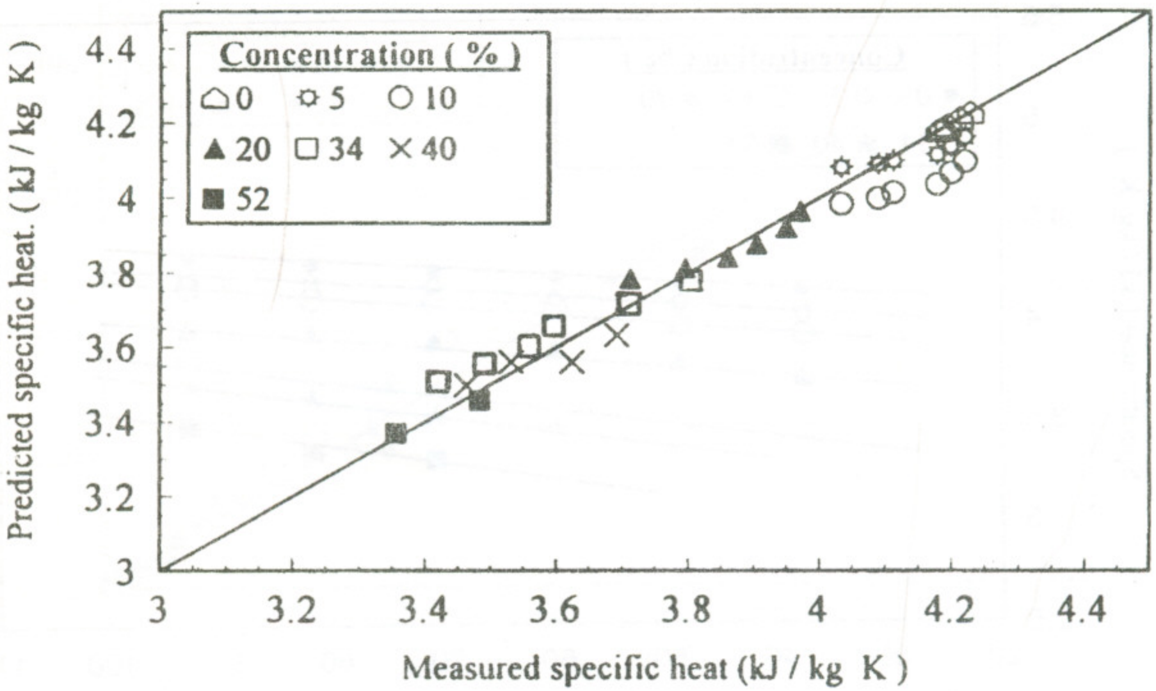

Figure 8 Comparison between measured and predicted specific heat values at different concentrations

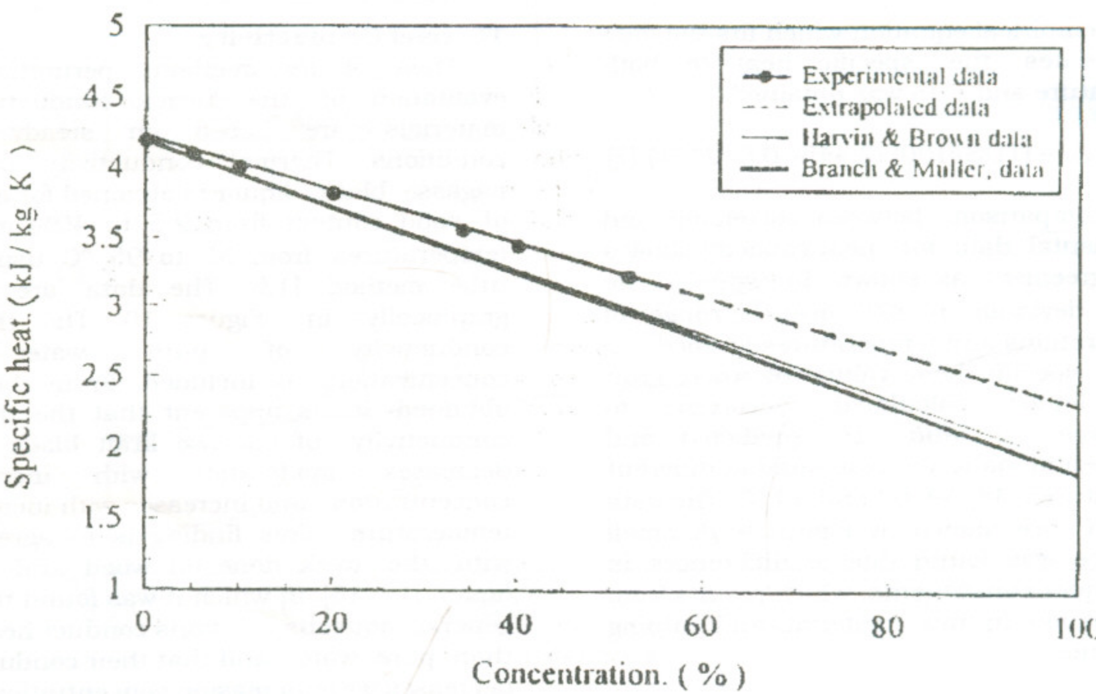

Figure 9 Comparison between predicted, Branch and Muller [12] , Harvin and Brown [16] specific heat values at 49°C for bagasse kraft black liquor

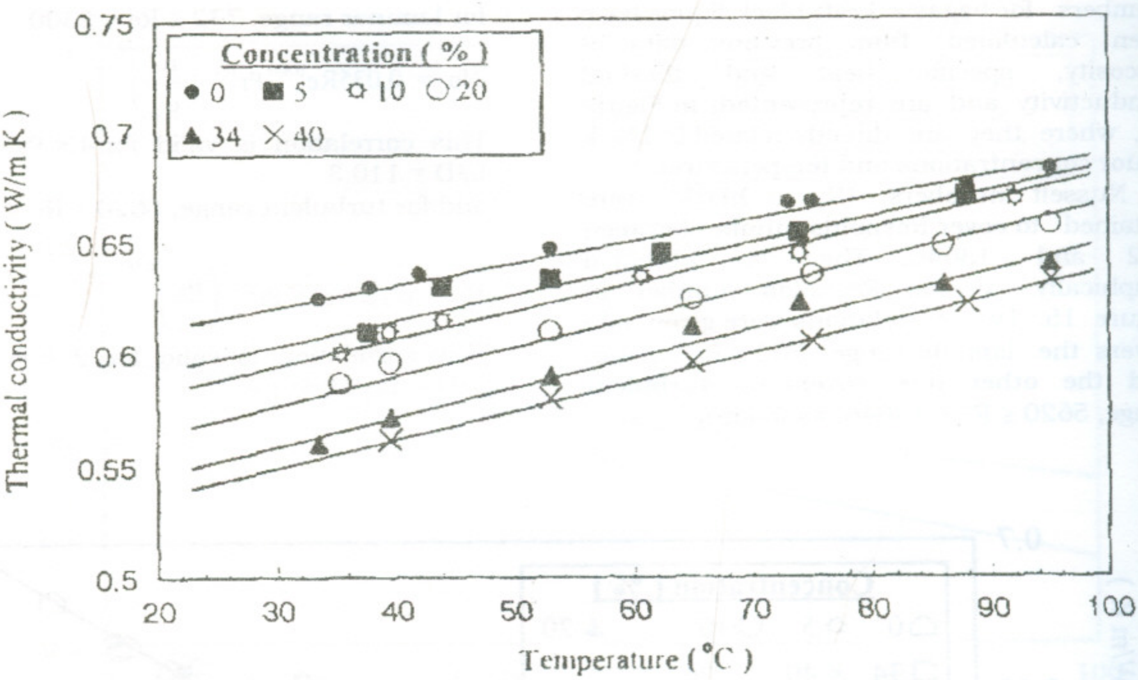

Figure 10 Effect of temperature on thermal conductivity at different concentration bagasse kraft black Liquor

An empirical equation was derived to fit the data and relate the thermal conductivity to both temperature and TDS. This equation was found to be:

$$K = k_{water} - (TDS/100)\,(0.2595 - 0.0015T) \quad (8)$$

A Comparison between measured and predicted thermal conductivity values from Equation 5 is shown in Figure 11. The results revealed that the measured and the predicted thermal conductivity values are identical, with a deviation of ± 2.5% over the ranges of temperatures and concentrations studied.

A comparison between the present study and that of Reference 12 for wood kraft black liquor, was carried out at different temperatures 39.5, 53, 74 and 95 °C. Figure 12 shows this comparison at 95 °C. A small difference may be due to the difference in black liquor constituents which result from the difference in pulping conditions, raw materials and method used in determination of thermal conductivity.

Heat Transfer Coefficient

The heat transfer coefficients "h" of bagasse kraft black liquor are obtained for the range of Reynolds number of 732 - 13646. The data is shown graphically in Figure 13, which is a plot of heat transfer coefficient versus Reynolds number "Re". The figure shows that there are three regions of flow,

- laminar flow; $Re \leq 2300$
- transient flow; $2300 < Re < 5620$
- turbulent flow; $Re \geq 5620$

The heat transfer coefficient was found to increase with increasing Reynolds number.

Coefficients for heat transfer in a fluid are often correlated partly in term of specific heat (Cp), viscosity (μ) and thermal conductivity (k) of the fluid brought together in a dimensionless group, Prandtl number ($Pr = Cp\mu/k$). The three quantities involved in the Prandtl number are properties which become fixed when the state of concentration and temperature of a liquor is fixed. Thus the Prandtl number will have a particular value characteristic of a liquor at a particular concentration and temperature. The Prandtl numbers for bagasse kraft black liquor have been calculated from previous data of viscosity, specific heat and thermal conductivity and are represented in Figure 14, where they are directly related in black liquor concentrations and temperatures.

Nusselt numbers, (Nu = hD/k), were obtained to cover Reynolds number between 732 and 13646. They are obtained graphically versus Reynolds number in Figure 15. Two correlations were given, one covers the laminar range, $732 \le Re \le 2300$, and the other one covers the turbulent range, $5620 \le Re \le 13646$, as follows:

for laminar range, $732 \le Re \le 2300$

$$Nu = 0.035 Re^{0.694} Pr^{0.3} \left(\frac{\mu_b}{\mu_w}\right)^{0.14} \quad (9)$$

This correlation is valid for $4 < Pr < 30$ and L/D = 110.3

and for turbulent range, $5620 \le Re \le 13646$

$$Nu = 0.126 Re^{0.525} Pr^{0.3} \left(\frac{\mu_b}{\mu_w}\right)^{0.14} \quad (10)$$

This correlation is valid for $2 < Pr < 6$ and L/D = 110.3

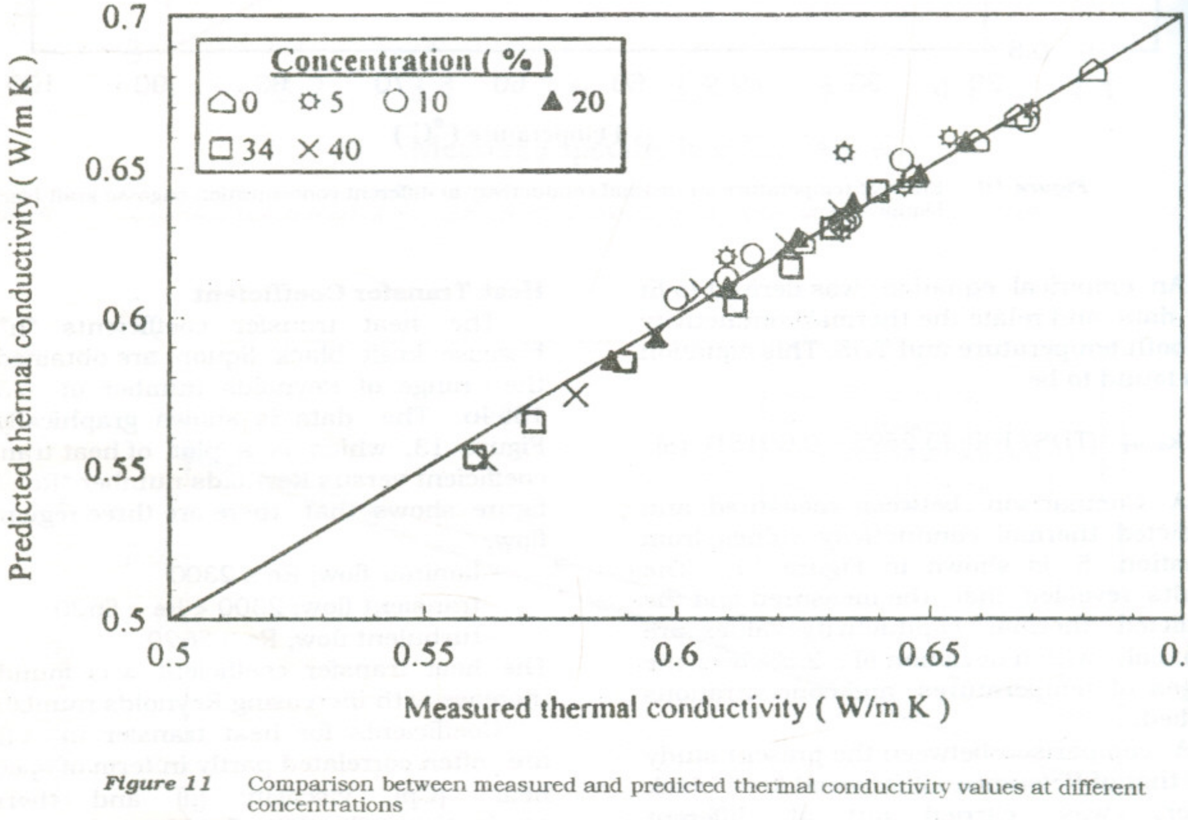

Figure 11 Comparison between measured and predicted thermal conductivity values at different concentrations

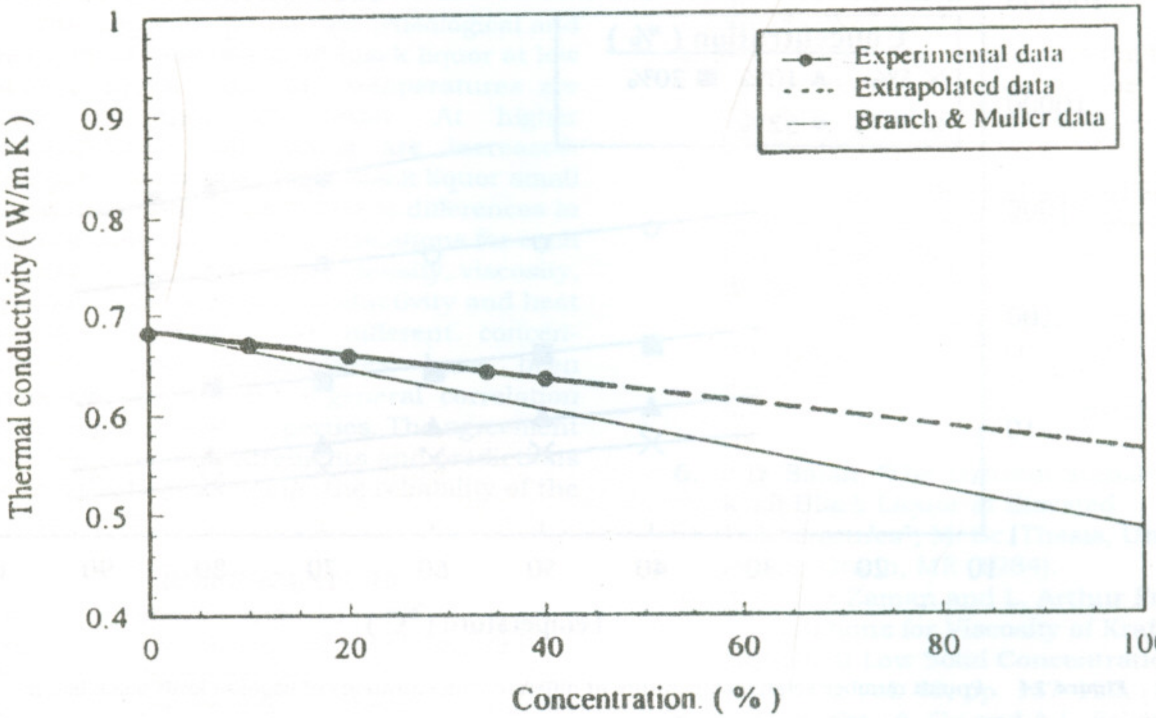

Figure 12 Comparison between predicted and, Branch and Muller [12] thermal conductivity values at 95 °C for bagasse kraft black liquor

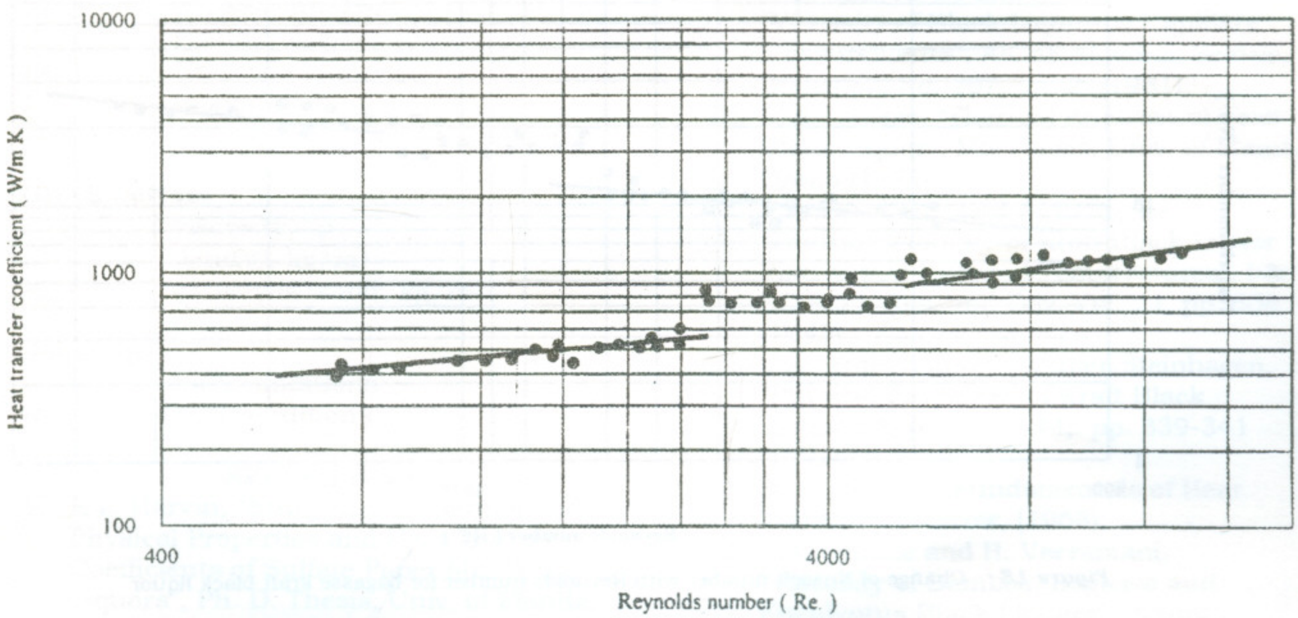

Figure 13 Change of heat transfer coefficient with Reynolds for bagasse kraft black liquor

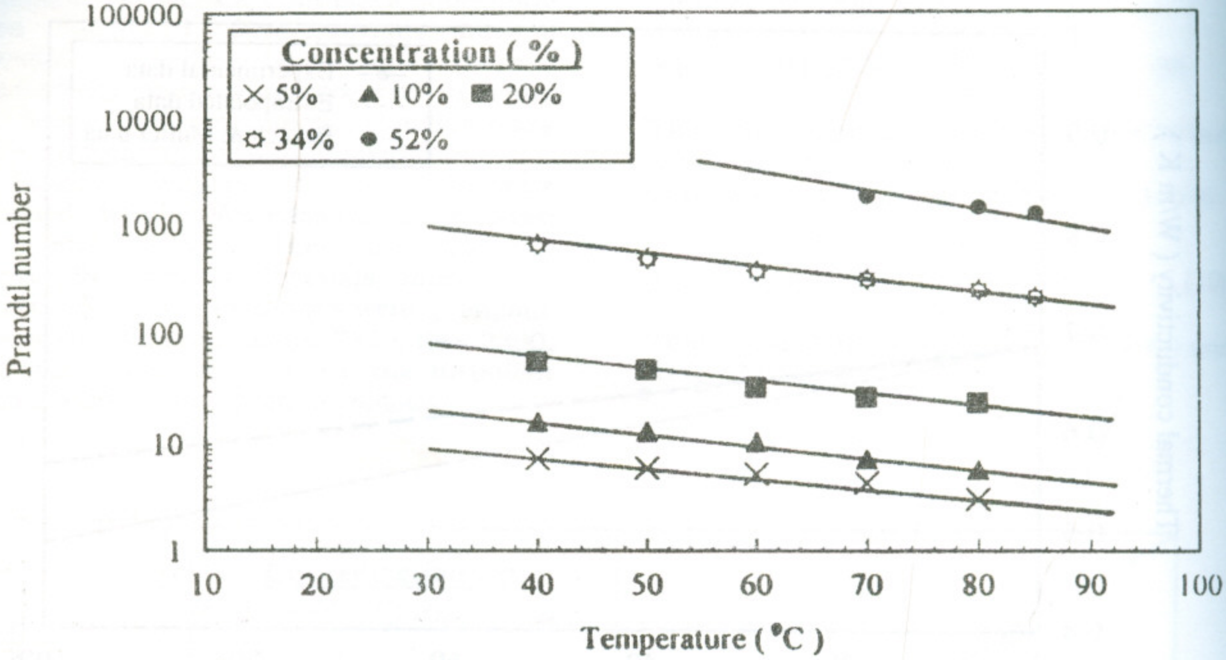

Figure 14 Prandt number versus temperature at different concentrations of bagasse kraft black liqour

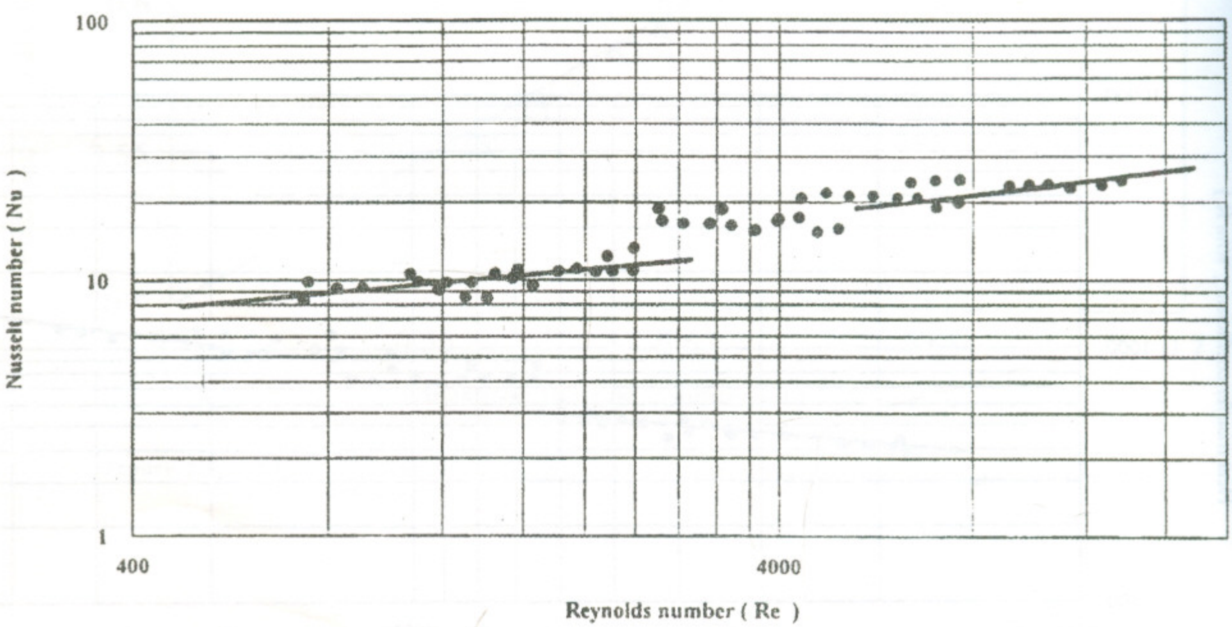

Figure 15 Change of Nusselt number with Reynolds number for bagasse kraft black liquor

CONCLUSIONS

The physical properties (rheological and thermal) of bagasse kraft black liquor at low concentrations and low temperatures are close to that of water. At higher concentrations all values are increased. Compared with wood kraft black liquor small differences were found due to differences in the raw materials used. Correlations for each physical properties namely density, viscosity, specific heat, thermal conductivity and heat transfer coefficient at different concentrations and temperatures have been proposed as well as a general correlation gathering all these properties. The agreement between the measurements and predictions is excellent, confirming the reliability of the correlations.

NOMENCLATURE

Cp	specific heat, kJ/kg K
Cp_{water}	specific heat of water, kJ/kg K
D	diameter, m
h	convection heat transfer coefficient, W/m K
k	thermal conductivity, W/m K
k_{water}	thermal conductivity of water, W/m K
L	characteristic length, m
Nu	Nusselt number
Pr	Prandtl number
Re	Reynolds number
T	temperature, K
TDS	total dissolved solids

Greek Letters

ρ	viscosity, cp
ρ	density, kg/m^3
ρ_{water}	density of water, kg/m^3

Subscript

b	bulk conditions
w	wall conditions

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مقاييس إنتقال الحراره والمائع للسائل الأسود من مصاص القصب

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ملخص البحث

ينتج السائل الأسود من صناعة لب الورق , وللأغراض الصناعية والبيئية يجب إسترجاع المواد الكيميائية والطاقة عن طريق حرق السائل الأسود المركز . وقد إختص البحث بقياس عوامل إنتقال الحرارة للسائل الأسود المتخلف من صناعة لب الورق من المصاص بطريقة الكرافت .و تشمل هذه العوامل الكثافة ، اللزوجة ، الحرارة النوعية، التوصيل الحراري ومعامل الإنتقال الحراري. هذه العوامل إما غير متوافرة في المراجع العلمية للأنواع المختلفة للسائل الأسود أو غير كاملة.

وقد تم نمذجة النتائج العملية لهذه العوامل لتركيزات من ٢,٥% الي ٥٢% ودرجات حرارة متغيرة من ٢٠م الي ٩٠م والمعادلات التى تجمع كل هذه العوامل فى حالة السريان الموازى و السريان الدوامى كالآتى :

السريان الموازى

$$Nu = 0.035\,\text{Re}^{0.69}\,\text{Pr}^{0.3}\left(\mu_b/\mu_w\right)^{0.14}$$

وهذه المعادلة صالحة للمدى **4 < Pr >30 and L/D = 11.03**

السريان الدوامى

$$Nu = 0.126\,\text{Re}^{0.52}\,\text{Pr}^{0.3}\left(m_b/m_w\right)^{0.14}$$

وهذه المعادلة صالحة للمدى **2< Pr >6 and L/D = 11.0**