University of Alberta

Solid-Liquid Mass Transfer in a Rotary Drum

by

Trevor Gerard Parsons ©

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Name of Author: Trevor Gerard Parsons

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6 Carroll Street

Glace Bay, Nova Scotia

B1A 3B3

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University of Alberta

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled Solid-Liquid Mass Transfer in a Rotary Drum submitted by Trevor Gerard Parsons in partial fulfilment of the requirements for the degree of Master of Science.

Dr. M.R. Gray
(supervisor)

Dr. J.H. Masliyah
(co-supervisor)

Dr. K.T. Chuang

Dr. H. Henein

May 25, 1995

for my parents

for their encouragement and support, always.

ABSTRACT

Hydrocarbon contamination of soil is a potential health and environmental hazard. Several methods can be used to remove contaminants from soil. One method which is potentially effective and efficient is to mix the contaminated soil in a rotary-drum bioreactor with water, nutrients and bacteria. As the hydrocarbons dissolve they are degraded by the bacteria. When the hydrocarbons are solid, as in the case of poly-nuclear aromatics, dissolution of the hydrocarbons from the solid to the liquid phase is the rate limiting step in the biodegradation process.

This study examined the solid-liquid mass transfer coefficient, k_s, of a model compound (β-naphthol) in a sand-water slurry. The mean particle size of both the sand and β-naphthol was 4.6 x 10^{-4} m. The effects of the different parameters (drum rotating speed, slurry holdup, and solids volume fraction) on the dissolution process were investigated. The operating ranges for the three parameters were: drum rotating speed - 0.33 to 15 rpm; slurry holdup - 4.4 to 17 %; and solids volume fraction - 0 to 0.62. The mass transfer coefficient increased with increasing rotational speed of the drum in the range 0.5 x 10^{-5} to 4.5 x 10^{-5} m s^{-1}. Two types of slurry motion were observed in the small drum; well mixed slurry flowing over the baffles and segregation of solids on the baffles. The mass transfer coefficient in the former regime correlates fairly well with the Froude number. This correlation should be useful for scale-up of mass transfer processes involving slurries in rotary drums. The present study extends the results of Miwa et al. (1991) to the lower range of Froude number.

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NOMENCLATURE

A	surface area of the β-naphthol particles, m^2
Ab	absorbance
C	concentration of β-naphthol in water, kg m^{-3}
C_b	copper ion concentration in bulk liquid, mol m^{-3}
C_i	initial concentration of β-naphthol in water, kg m^{-3}
C_o	copper ion concentration on the particle surface, mol m^{-3}
C_s	solubility concentration of β-naphthol in water, kg m^{-3}
D	diameter of the drum, m
D_{aqu}	diffusivity of β-naphthol in water, m^2 s^{-1}
D_{mix}	diffusivity of slurry, m^2 s^{-1}
D_p	particle diameter, m
D_v	diffusivity, m^2 s^{-1}
d_h	hydraulic diameter, m
d_{pi}	diameter of particle i, m
Fr_{cr}	critical Froude number
Fr_1	Froude number, Miwa et al.
Fr_2	Froude number, Gray et al.
Fr_3	Froude number, Masliyah et al.
Fr_4	Froude number, present study
g	gravitational constant, m s^{-2}
h	height of the slurry in the drum, m
k_c	mass transfer coefficient, Harriott, m s^{-1}

k_L	mass transfer coefficient, Miwa et al., m s^{-1}
k_L'	apparent mass transfer coefficient, m s^{-1}
k_La	volumetric mass transfer coefficient, s^{-1}
$(k_La)'$	modified volumetric mass transfer coefficient, s^{-1}
k_s	solid-liquid mass transfer coefficient, m s^{-1}
m	mass of β-naphthol particles, kg
N	rotational rate of the drum, s^{-1}
N_{cr}	critical rotational rate of the drum, s^{-1}
N_p	number of β-naphthol particles
Re_1	Reynolds number, slip velocity equation
Re_2	Reynolds number, Gray et al.
r_p	mean radius of the β-naphthol particles, m
S_s	density ratio, ρ_s/ρ_w
Sh	Sherwood number
Sh_1	Sherwood number, slip velocity equation
Sc	Schmidt number
Sc_1	Schmidt number, slip velocity equation
t	time, s
V	volume of slurry, m^3
V_L	volume of liquid, m^3
V_s	volume of sand, m^3
V_ω	velocity of the drum wall, m s^{-1}
v_t	terminal velocity, m s^{-1}

Greek

α	solids volume fraction
β_i	shape factor in terms of the surface area of particle, i
θ	inclination of the drum to the vertical
λ	wavelength, nm
μ	viscosity, kg m^{-1} s^{-1}
μ_{mix}	slurry viscosity, kg m^{-1} s^{-1}
μ_w	water viscosity, kg m^{-1} s^{-1}
ρ	density, kg m^{-3}
ρ_{mix}	slurry density, kg m^{-3}
ρ_p	density of β-naphthol, kg m^{-3}
ρ_s	solids (sand) density, kg m^{-3}
ρ_w	water density, kg m^{-3}
ψ_i	shape factor in terms of the volume of the particle, i

1. INTRODUCTION.

Hydrocarbons can be spilled at every stage of the exploration, transportation, refining and end use of petroleum and petrochemical products. Spills often result in residual soil contamination. Hydrocarbon contamination of soil is a major problem because the hydrocarbons can migrate into surrounding ground water. These contaminants should be removed from the soil before they dissolve into the ground water. If the contaminants dissolve into the ground water, a combination of ground water and soil treatment must be used to remove them.

Several remediation methods can be used to remove the hydrocarbon contaminants from the soil. These different remediation methods can be classified into four groups: physical, chemical, thermal, and biological.

Physical treatment methods work by exploiting differences in physical characteristics (density, vapour pressure, adsorption potential) to separate the contaminants from the soil. Physical treatment methods do not destroy or chemically alter the contaminants. Two physical treatment methods are soil vapour extraction and soil washing (Hopper, 1989). Soil vapour extraction uses vacuum pumps or air blowers to produce an air flow through the contaminated soil. The contaminants desorb from the soil into the air and the air is then cleaned of these contaminants by carbon adsorption or catalytic incineration. Soil vapour extraction is only feasible for contaminants with a low vapour pressure such as volatile organic compounds (VOC). Soil washing involves removing the soil from the ground and washing the soil in hoppers with a solvent or surfactant solution that will solubilize the contaminants. The contaminants are then separated from the solvent and destroyed.

Chemical treatment destroys or chemically alters the contaminants to decrease their toxicity or mobility. Two examples are in-situ oxidation and ultraviolet oxidation (Long, 1993). In-situ chemical oxidation uses hydrogen peroxide as the oxidizing agent. The soil must be highly permeable for the peroxide to reach the contaminants for in-situ chemical oxidation. The oxidation reaction must be controlled so it does not reach combustion rates.

Thermal treatment uses heat, which chemically or physically alters the contaminants. Two methods of thermal treatment include incineration and thermal desorption (Long, 1993). Incineration involves removing the soil from the ground and burning it in rotary kilns or fluidized beds. This converts the hydrocarbons in the soil to water and carbon dioxide. Thermal desorption is a process that operates at lower temperatures than incineration. It vaporizes the contaminants from the soil and then recondenses them as liquids.

Biological remediation, or bioremediation, uses the soil's naturally occurring bacteria, or added bacteria, to decompose the contaminants. Unlike some other methods, bioremediation destroys organic contaminants. Incineration also destroys organics but concentrates the heavy metals in the residue, while physical treatment methods remove contaminants but do not destroy them. In bioremediation, nutrients can be added to the soil to aid the bacteria in decomposing the hazardous waste. The bacteria degrade the hazardous organic compounds into water and carbon dioxide.

Landfarming, in-situ bioremediation and pile bioreactors are three examples of bioremediation techniques. Landfarming involves treating the soil in above-ground treatment beds, with regular aeration and nutrient addition. In-situ treatments involve injecting nutrients and enriched bacterial populations into the soil. Pile bioreactors involve spraying nutrients and bacteria onto a pile of excavated soil. The runoff is collected and recycled, and aeration may also be provided. In all three methods there is no effective mixing in the soil, which creates problems for contact between bacteria and contaminants and for oxygen transfer to the bacteria. One solution to this problem is to process the soil as slurry in water, with mechanical agitation to provide mixing.

One can use either an agitated tank bioreactor or a rotary drum bioreactor for the treatment of soil slurries. An agitated tank is a vertical tank that uses an impeller for mixing and an air sparger for aeration. A rotary drum uses internal baffles or lifters for mixing. In either case, the soil is mixed with water to form a slurry. Bioreactor operation allows control over pH, contact time of the bacteria with the hydrocarbons, temperature, and supply of nutrients. Agitated bioreactors of any type also provide better mixing and aeration than heap treatment, and better recycling of liquids and slurries.

The disadvantage with an agitated tank bioreactor is that large volumes of water, (upwards of 4:1 weight ratio of water to soil), are required to suspend the soil mixture. Even with this large ratio of water to soil, power requirements are high in order to keep the soil suspended in the slurry. In contrast, rotary drums provide high aeration rates and effective mixing at a high solids content.

There are three different ways that hydrocarbons can be present in the soil: as a separate liquid or solid phase, as a film on the surface of the soil particles, or as a layer adsorbed on the internal surface of the soil particle. Hydrocarbons in the separate solid or liquid phase and those that exist as a surface film are solubilized by dissolution. Intra-particle hydrocarbon desorbs, then diffuses to the surface and into the water. The main limitations to dissolution are the low solubility in an aqueous phase and the liquid-film resistance to mass transfer. Bacteria utilize polynuclear-aromatic hydrocarbons only in the water soluble state. For example, the dissolution of the hydrocarbons from the solid to the aqueous phase is the rate limiting step in the biodegradation of poly-nuclear aromatics such as naphthalene (Volkering et al., 1992). The mass transfer in this rate limiting step requires further research.

The objective of this study is to determine the appropriate dimensionless groups that influence the dissolution of a tracer compound in a slurry in a rotary drum. The effect of varying different parameters (drum rotational speed, slurry holdup, and solids volume fraction) on the solid-liquid mass transfer coefficient, k_s, will be studied. A correlation will be developed to predict the mass transfer coefficient, k_s, using appropriate dimensionless groups as a tool for scale-up of rotary drum bioreactors.

2. LITERATURE REVIEW.

Rotary drums are used frequently in industry, most often as rotary kilns. The heat transfer and bed motion aspects of rotary kilns have been extensively studied (Barr et al. 1989). Rotary drums are used on a very large scale for mixing of slurries in the hot water extraction of bitumen from the Athabasca tar sands (Carrigy, 1963), however, mass transfer in slurries in rotary drums has not been widely studied.

While there is little information available on solid-liquid mass transfer in slurries in rotary drums, there are data and correlations for solid-liquid mass transfer in agitated or stirred tanks (Boon-Long et al. 1978, Lal et al. 1988). The problem with determining solid-liquid mass transfer in slurries in rotary drums is finding suitable dimensionless groups that correlate all the operating parameters, e.g., drum rotational speed, slurry holdup, and slurry density and viscosity.

2.1 Solid-Liquid Mass Transfer in an Agitated Tank.

Many studies have been conducted concerning solid-liquid mass transfer in agitated or stirred tanks, although studies of crystallization are much more numerous. Harriott (1962) conducted a very extensive study on solid-liquid mass transfer coefficients in agitated, baffled tanks. Harriott found that the mass transfer coefficients were 1.5 to 8 times higher than those predicted from the slip velocity theory, if terminal velocity is used in the calculation of Reynolds number. The equation used in the slip velocity theory for predicting the mass transfer coefficient is:

$$Sh_l = 2 + 0.6(Re_l)^{0.5} (Sc_l)^{0.33} \qquad (2\text{-}1)$$

Equation (2-1) was obtained from Ranz and Marshall (1952). The dimensionless numbers (Sherwood number, Sh_l, Reynolds number, Re_l, and Schmidt number, Sc_l) are defined as:

$$Sh_l = \frac{k_c D_p}{D_v} \qquad (2\text{-}2)$$

$$Re_l = \frac{D_p v_t \rho}{\mu} \qquad (2\text{-}3)$$

$$Sc_l = \frac{\mu}{\rho D_v} \qquad (2\text{-}4)$$

where k_c is the mass transfer coefficient, D_p is the particle diameter, D_v is the diffusivity, v_t is the terminal velocity, ρ is the density of the fluid, and μ is the viscosity of the surrounding fluid.

When the film layer thickness is small relative to the diameter of the particle (large Sherwood number), the slip velocity prediction for the mass transfer coefficient and Harriott's findings are similar. The difference in mass transfer coefficient comes about for small or low density particles (small Sherwood number). Harriott states that this is due to the transient effects of eddies coming near the surface.

Harriott studied a variety of parameters, including stirrer location and speed, particle size, diffusivity, viscosity, density difference between the solute and solvent, and volume fraction of the solids.

Harriott found that the mass transfer coefficient was proportional to the 0.5 power of the turbine speed for large particles (larger than 100 μm). The exponent decreased as the particles become smaller and it reached a minimum of 0.3 for particles that are 15 μm in diameter. Harriott varied the solids volume fraction from 0.12 to 5.57 volume percent. The mass transfer coefficients varied from 0.0145 to 0.0149 cm s^{-1}, and Harriott found no apparent trend to the data at such low solids volume fractions where particle-particle interactions were unimportant.

2.2 Diffusion-Controlled Liquid-Solid Reaction in a Rotary Drum.

Miwa et al. (1991) used a rotary drum to follow the time course of cementation of cuprous copper ions onto iron particles. Knowing that the diffusion rate of Cu^{2+} was the controlling factor in the net rate of cementation of the copper ions, they applied the boundary-layer theory to obtain the following equation:

$$\frac{dC_b}{dt} = - k_L a \; (C_b \; - C_o) \qquad (2\text{-}5)$$

where C_b and C_o are the copper ion concentrations in the bulk liquid and on the iron particle surface, respectively, and $k_L a$ is the volumetric mass transfer coefficient and is defined as:

$$k_La = \frac{\alpha}{1-\alpha} \frac{4\pi \sum_{i=1}^{n} \beta_i (\frac{d_{pi}}{2})^2}{\frac{4}{3}\pi \sum_{i=1}^{n} \psi_i (\frac{d_{pi}}{2})^3} k_L \qquad (2\text{-}6)$$

where α is the solids volume fraction, β_i is the shape factor in terms of the surface area of particle i, ψ_i is the shape factor in terms of the volume of particle i, d_{pi} is the diameter of particle i, n is the number of particles, and k_L is the mass transfer coefficient. ψ_i in equation form is:

$$\psi_i = \frac{\text{actual volume of particle i}}{\text{volume of equivalent sphere}} \qquad (2\text{-}7)$$

and β_i is:

$$\beta_i = \frac{\text{actual surface area of particle i}}{\text{surface area of equivalent sphere}} \qquad (2\text{-}8)$$

In their experimental studies they varied solids volume fraction, α, particle diameter, d_p, the rotational speed of the drums, and the inclination of the drums. They used a modified volumetric mass transfer coefficient, $(k_La)'$, to correct for the effects of the solids volume fraction on the volumetric mass transfer coefficient, k_La, as follows:

$$(k_La)' = k_La \frac{1-\alpha}{\alpha} \qquad (2\text{-}9)$$

They also found that the nominal particle diameter, d_p, had an effect on $(k_La)'$ so they defined a new term, k_L', the apparent mass transfer coefficient, which is defined as:

$$k_L' = d_p \, (k_L a)' \qquad (2\text{-}10)$$

Restating equation (2-5) using k_L' instead of $k_L a$, we have:

$$\frac{dC_b}{dt} = - \frac{k_L' \, \alpha}{d_p \, (1 - \alpha)} (C_b - C_o) \qquad (2\text{-}11)$$

Miwa et al. assumed that the governing dimensionless group was Froude number, defined as:

$$Fr_1 = N^2 \frac{D}{g} \qquad (2\text{-}12)$$

where N is the rotational rate of the drum (s^{-1}) and D is the drum diameter. Their plot for k_L' versus Fr_1 is shown in Figure 2-1.

At high Froude numbers there is a sharp decrease in the mass transfer coefficient because in their experimental runs Miwa et al. exceeded the critical Froude number, Fr_{cr} (the vertical line on the graph) for their rotating drums. They used the following equation to define the critical rotational rate, N_{cr}:

$$N_{cr} \geq \frac{1}{2\,\pi} \sqrt{\frac{2\,g\,\sin\,\theta}{D}} \qquad (2\text{-}13)$$

where θ is the inclination of the reactor to the vertical and D is the diameter of the drum. Substituting the above equation into equation (2-12) we obtain an expression for Fr_{cr}:

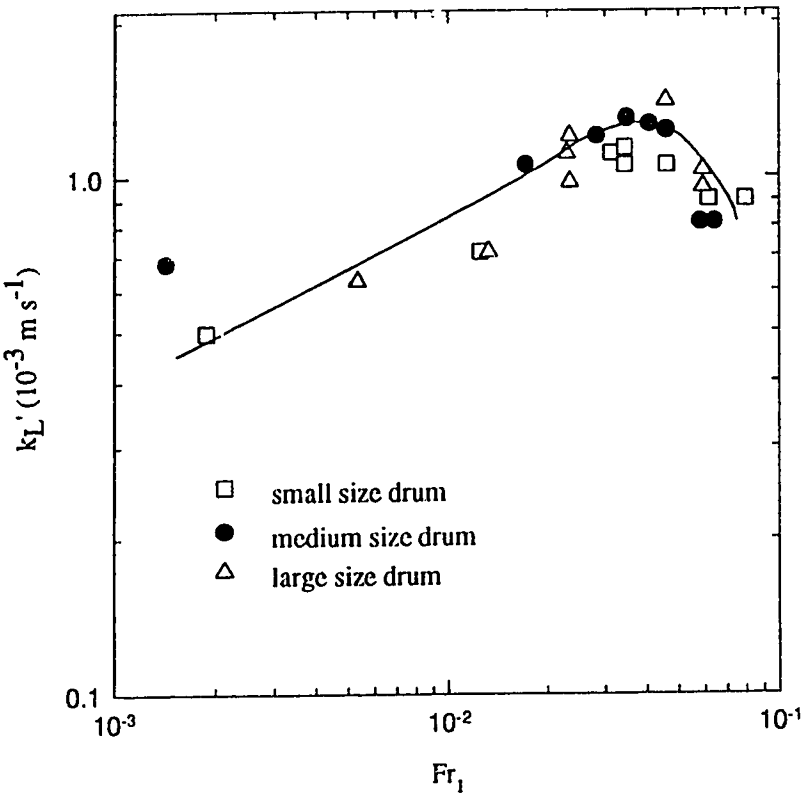

Figure 2-1. Variation of k_L' with Fr_l number. Miwa et al. results.

$$Fr_{cr} = 0.0507 \sin\theta \qquad (2\text{-}14)$$

2.3 Liquid-Side Mass Transfer Coefficients for Gas-Slurry Mass Transfer in a Rotating Drum.

Gray et al. (1993) studied the effects of drum rotational speed, liquid holdup and volume fraction solids on the liquid-side mass transfer coefficient, k_L, for oxygen transfer.

First they studied the dependence of k_L on the Reynolds number, defined as:

$$Re_2 = \frac{d_h \, V_\omega \, \rho}{\mu} \qquad (2\text{-}15)$$

where d_h is the hydraulic diameter, V_ω is the velocity of the drum wall, and ρ and μ are the density and viscosity, respectively. They found that this expression (Re_2) did not correlate the effect of the drum rotational speed and liquid holdup on the liquid-side mass transfer coefficient, k_L. A plot of mass transfer coefficient versus Reynolds number (Re_2) showed two trends. At constant liquid holdup, the mass transfer coefficient increased linearly with Re_2 as rotation speed was increased. The opposite trend was observed at constant rotation when liquid holdup was varied.

Gray et al. used an expression for Froude number that correlated the effects of liquid holdup and rotational speed on the mass transfer coefficient fairly well. This expression is:

$$Fr_2 = \frac{V_\omega}{(g \, h)^{1/2}} \qquad (2\text{-}16)$$

where h is the height of the slurry in the drum.

2.4 General Definition of Froude Number.

So far there have been two different expressions used to define Froude number: one used by Miwa et al., defined in equation (2-12), and one used by Gray et al., defined in equation (2-16). Equation (2-12) allows for the variation in N, the rotational rate of the drums and the drum diameter, and equation (2-16) allows for the variation in rotational speed of the drum, V_ω, and the liquid hold-up, h. However, neither expression considers the variation of density.

Masliyah et al. (1992) used a semi-empirical correlation to explain the effects of slurry flow rate, feed solids concentration, particle settling velocity and drum rotational speed on the hold-up solids concentration in their study on the flow of slightly settling slurries in a horizontal rotary drum. In their correlation they used a Froude number, which they defined as:

$$Fr_3 = \frac{V_\omega}{\sqrt{g\ D\ (S_s - 1)}} \tag{2-17}$$

where V_ω is the rotary drum peripheral speed, D is the drum diameter, and S_s is the density ratio, ρ_s/ρ_w, (ρ_s is the solids density and ρ_w is the carrier fluid density). In Masliyah et al. the hold-up was a dependent variable and was not used in the above equation. However, in this study, h or holdup is an independent variable and can be included in the above equation as a characteristic length scale. The following expression takes into account the rotational speed, holdup, and density difference between the solid and liquid phases:

$$Fr_4 = \frac{V_\omega}{\sqrt{2\ g\ h\ (S_s - 1)}} \tag{2-18}$$

3. MATERIALS & EXPERIMENTAL METHOD.

3.1 Selection of Tracer for Dissolution Studies.

To measure the solid-liquid mass transfer coefficient in a rotating drum, a solid tracer was added to a sand-water slurry and dissolution was determined as a function of time. The solid tracer was selected for its low solubility in water, its mechanical strength, and for ease of measuring its concentration in solution. β-naphthol was found to be a suitable tracer for these experiments. A list of the properties of β-naphthol is given in Table 3-1.

Table 3-1. Properties of β-naphthol at 20 °C.

	ρ_p, kg m^{-3}	Solubility in water, g L^{-1}	D_p, diameter of particles, m	D_{aqu}, diffusivity in water, m^2 s^{-1}
β-naphthol	1217	0.74	4.62×10^{-4}	1.04×10^{-9}

The density of β-naphthol was obtained from Perry and Green (1984). The diffusivity and solubility were both obtained from Moyle & Tyner (1953).

3.2 Rotating Drum Experiments.

The small drum that was used was made of acrylic and was fitted with four acrylic baffles. The large drum was made of stainless steel and was equipped with four stainless steel baffles. The width of the baffles for both drums was 10 % of the drum diameter. The dimensions of the drums are listed in Table 3-2.

Table 3-2. Dimensions of the Drums.

	Small Drum	Large Drum
Diameter, m	0.29	0.58
Length, m	0.308	0.90
Volume, m^3	0.020	0.24

Both drums were placed on rollers which were rotated, through a chain and gears, by a variable speed motor. Figure 3-1 shows the apparatus.

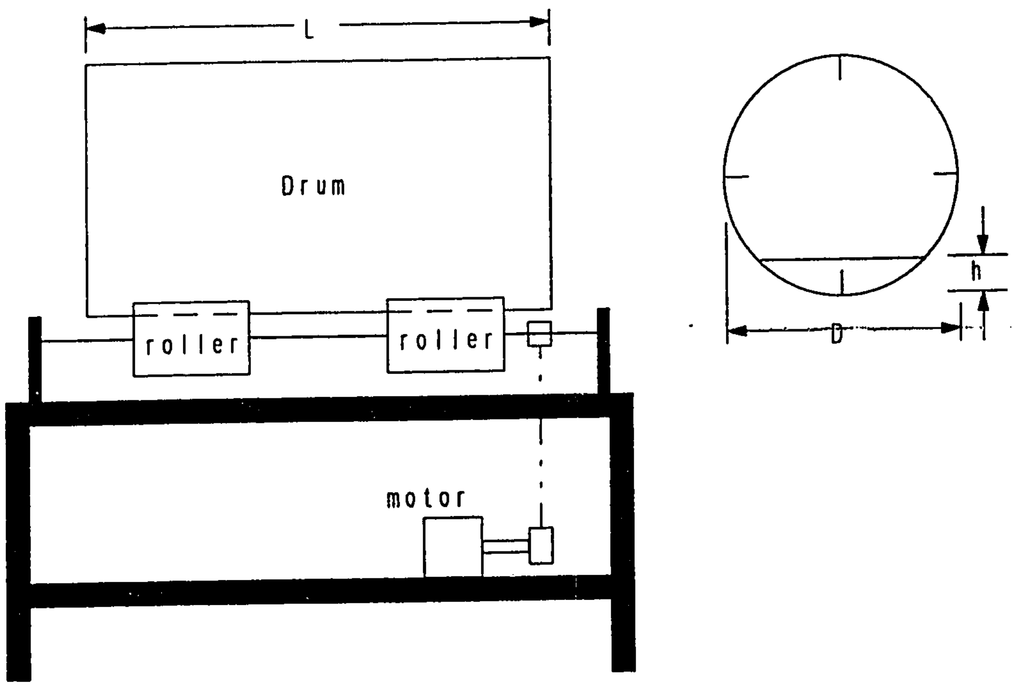

Figure 3-1. Schematic Diagram of the Drums.

The height, h, is the height of the slurry in the drum and it is the characteristic length scale used in the Froude expressions found in Chapter 4. The height, h, was measured directly, as shown in Figure 3-1. The rpm for both the small and large drums was measured by timing the rate of revolution of a mark on the drum. The range of operating conditions for the two drums is shown in Table 3-3.

Table 3-3. Operating Conditions of the Drums.

	Small Drum	Large Drum
Temperature, °C	20	20
R.P.M.	0.3-15	0.73-3.7
Slurry Holdup	4.4-17 %	4.4-8.7 %
Solids Volume Fraction	0-0.43	0.43

The material that was loaded in the drum consisted of sand, water, and the tracer compound β-naphthol. The base conditions for all experiments conducted in the small drum were 3 rpm, a slurry holdup of 8.7 % and a solids volume fraction of 0.43. The slurry consisted of 2 kg of sand, 1 kg of water and 0.2 g of β-naphthol. The silica sand had an average particle diameter of 4.6×10^{-4} m, and the range of mesh sizes used to sieve the sand were 35-40 mesh. The water was filtered using a reverse osmosis filtration system. The β-naphthol particles were crushed and sieved to match the particle size of the sand particles.

The duration of each experiment was 45 minutes. At least 5 samples were taken during each experiment. The samples were taken out of the drum with a scoop and placed in a Buchner funnel lined with Whatman #42 filter paper, with a retention of particles larger than 2.5 μm. The filtrate was collected and analyzed by UV spectrophotometer to calculate the absorbance.

An experiment was conducted to test if β-naphthol was absorbed onto the sand particles. A known concentration of β-naphthol was prepared in water. Sand was then added to make a slurry that had a solids volume fraction of 0.43. Samples were taken before the addition of sand and after for comparison. There was no drop in β-naphthol concentration after the addition of the sand to the water phase, therefore, adsorption was insignificant.

3.3. Standard Curves for Analyzing β-naphthol Concentrations.

Each aromatic compound has a characteristic absorbance spectrum. Figure 3-2 shows the absorbance spectrum from 200 to 400 nm for β-naphthol.

To obtain a standard curve for concentration versus absorbance, a known concentration of β-naphthol was prepared in water. This solution was then analyzed in a UV spectrophotometer for its absorbance spectrum. The absorbance at each major peak was recorded. Then the solution was diluted and measured again. In this way a graph can be set up of known concentration versus absorbance at a given wavelength, as

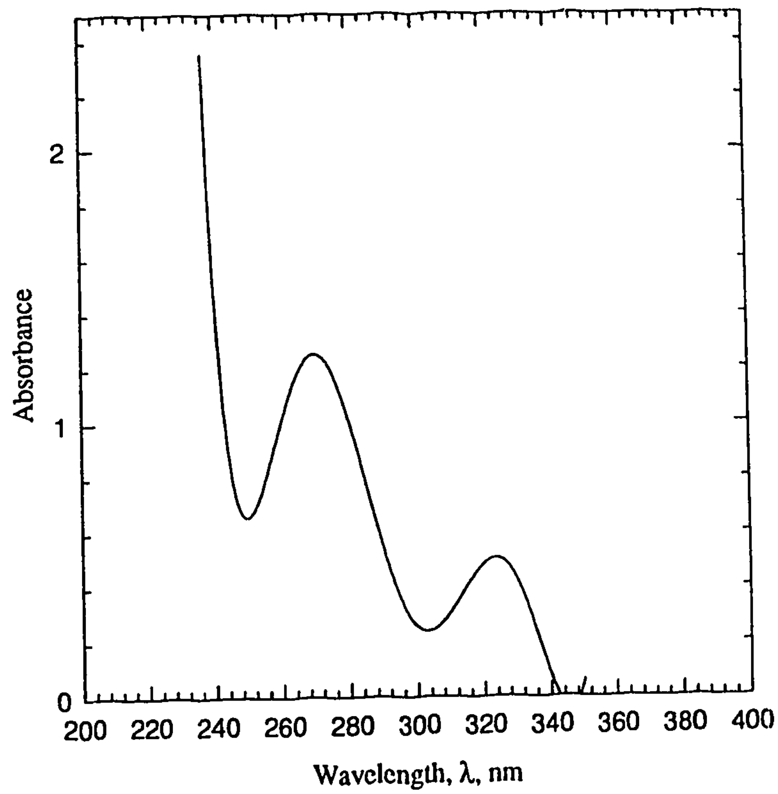

Figure 3-2. Absorbance Spectrum for β-naphthol in Water at a Concentration of 5.29×10^{-2} g L^{-1}.

shown in Figure 3-3.

All measurements used 3 cm^3 quartz cuvettes, with reverse-osmosis purified water as a reference. Table 3-4 lists the slope and intercepts for each wavelength.

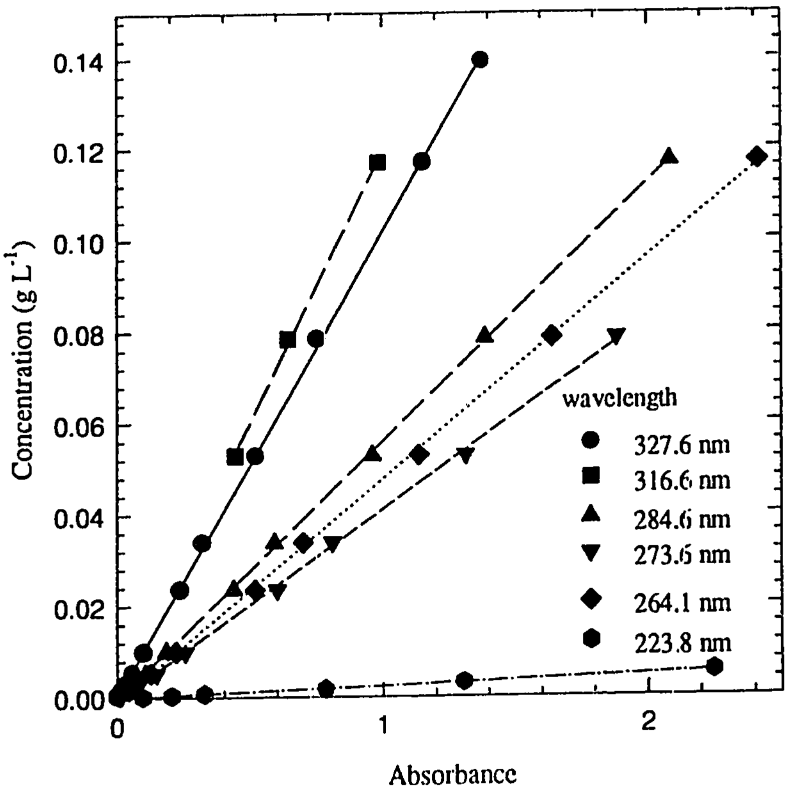

Figure 3-3. Standard Curves for β-naphthol Solutions in Water.

A wavelength of 327.6 nm was used because it allowed the widest concentration range for analysis of samples without dilution of samples. The relevant equation was:

$$C = 0.101\ Ab + 3.16 \times 10^{-4} \tag{3-1}$$

where C is the concentration and Ab is the absorbance obtained from the UV spectrophotometer.

Table 3-4. Slope and Intercept for Standard Curves for β-naphthol at each Wavelength.

Wavelength, λ, nm	Slope	y-intercept
327.6	0.102	3.15×10^{-4}
316.6	0.118	1.75×10^{-3}
284.6	0.0563	-2.72×10^{-4}
273.6	0.0414	-3.08×10^{-4}
264.1	0.0484	-6.34×10^{-4}
223.8	2.41×10^{-3}	-5.32×10^{-5}

3.4 Analysis of the Samples.

A Shimadzu UV-visible recording spectrophotometer UV-160 was used for measuring the absorbance of each sample. This absorbance was then compared to the concentration-absorbance standard curve to obtain the concentration of each sample. Table 3-5 shows typical data from one experiment.

The minimum amount of the β-naphthol that dissolved during the experiments was 18 % and the maximum was 70 %. The sand and water were mixed together in the drum for 10 minutes prior to the introduction of the β-naphthol particles. Sample #1 was taken before the introduction of the β-naphthol particles and is used as the initial reading (C_i).

Table 3-5. Sample Data from One Experiment. RPM of 15, slurry holdup of 8.7 %, solids volume fraction of 0.43.

Sample	Time, min	Absorbance at 327 nm	Concentration, g L^{-1}
1	0	0.073	0.0077
2	5	0.320	0.0329
3	10	0.505	0.0516
4	15	0.661	0.0674
5	25	0.939	0.0958
6	35	1.169	0.1191
7	45	1.354	0.1379

4. RESULTS & DISCUSSION.

4.1 Observations on Slurry Mixing

As mentioned in Chapter 2 there are two equations for Froude number which can be used to correlate the solid-liquid mass transfer coefficient, k_s, in a rotary drum. Each equation can only be used to describe one type of mixing that is occurring in the drum. One type of mixing is analogous to slurry flowing over a weir, as shown in Figure 4-1.

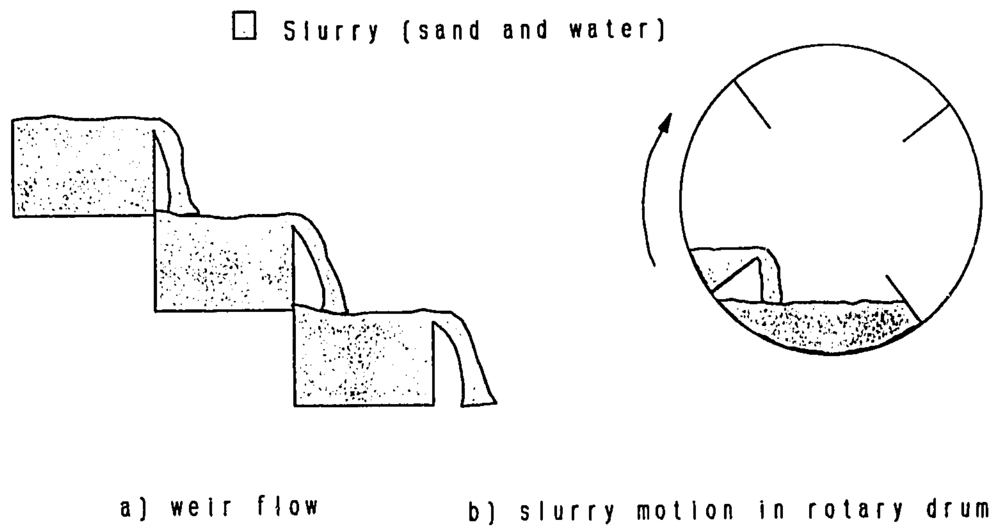

Figure 4-1. Comparison between flow over a weir and mixing in a rotary drum. Mixing at low slurry holdup and low solids volume fraction.

As shown in the diagram, the slurry flows over each baffle, as each baffle passes through the bottom of the rotation. The drum rotational speed controls the frequency of water to flow over the weirs (or baffles). The sand stays on the baffles throughout the rotation of the drum. A Froude expression that is appropriate to this type of mixing was stated in Chapter 2 and is repeated here:

$$Fr_2 = \frac{V_\omega}{\sqrt{2\ g\ h}} \tag{4-1}$$

In our experiment the manipulated variables in this expression are the height of the slurry, h, and the velocity of drum wall, V_ω.

Another type of mixing is where gravity effects dominate over the height of the slurry in the bottom of the drum. Figure 4-2 is a diagram of this type of mixing.

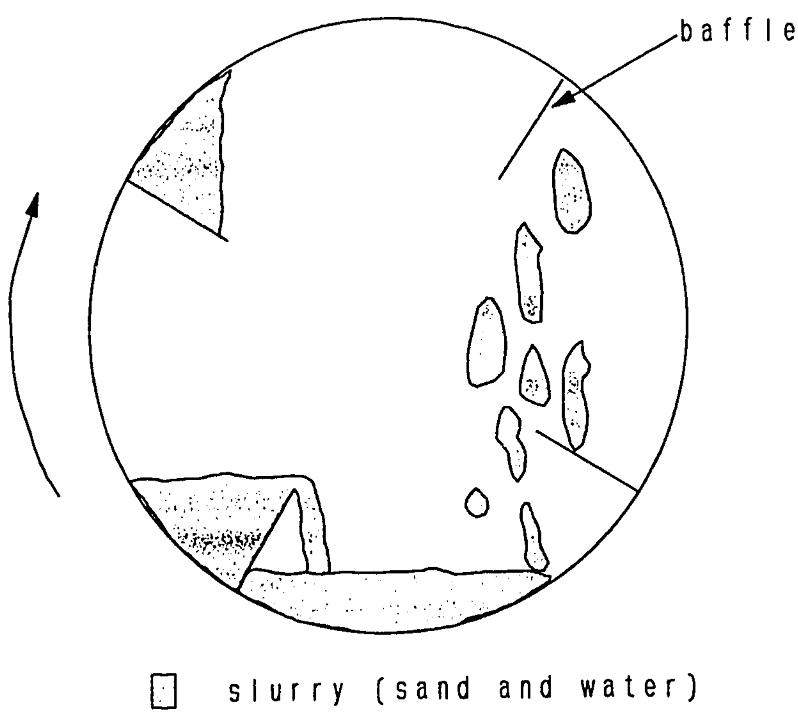

Figure 4-2. Slurry motion in a rotary drum. Mixing at high slurry holdup and high solids volume fraction, for the complete range of drum rotational speed.

The sand falls off of each baffle as shown in the diagram and is mixed at the bottom of the drum. In this type of mixing, drum diameter is more important than depth of slurry, therefore, the following expressions for Froude number are appropriate:

$$Fr_1 = N^2 \frac{D}{g} \tag{4-2}$$

$$Fr_3 = \frac{V_\omega}{\sqrt{g\ D\ (S_s - 1)}} \tag{4-3}$$

Unlike the expression for Fr_2, the two expressions stated above have no dependence on the slurry height, h. However, they are dependent upon the drum diameter, D. The Froude expression stated in equation (4-1) can be used for low rotational speeds, however, as the rpm approaches the critical rpm the analogy for weir flow mixing is not appropriate.

4.2 Observations on Dissolution Kinetics.

The solid-liquid mass transfer coefficient of suspended solids in a rotating drum has been measured by following the dissolution of β-naphthol as a function of time. Under dilute conditions, the mass transfer coefficient is defined as the constant of proportionality between the rate of dissolution and the driving force for dissolution. The governing differential equation describing the dissolution rate is given by:

$$A\ k_s\ (C_s - C) = V\ (1 - \alpha)\ \frac{dC}{dt} \tag{4-4}$$

where V is the slurry volume, α is the solids volume fraction ($\alpha = V_s/(V_s + V_L)$, V_s is the volume of sand and V_L is the volume of liquid), A is the surface area of the β-naphthol particles, k_s is the mass transfer coefficient, C_s is the maximum solubility concentration of β-naphthol in water, and C is the concentration of β-naphthol in water at time t.

The dissolution rate, as characterized by (dC/dt), of β-naphthol is highest when there is no solute dissolved (C=0), and the rate approaches zero when C is close to the saturation value, i.e. $C=C_s$. Assuming perfect mixing of β-naphthol throughout the sand-water mixture, and that the surface area, A, does not change appreciably as the solute dissolves, equation (4-4) can be integrated from C_i to C and time 0 to t, to give:

$$\ln \frac{C_s - C_i}{C_s - C} = \frac{k_s A}{V(1-\alpha)} t \qquad (4\text{-}5)$$

Plotting the logarithmic term versus time, the slope of the line can be used to calculate the mass transfer coefficient, k_s. Figure 4-3 shows results from a typical experiment, where the total mass of the dissolved β-naphthol is not high, i.e., A is held fairly constant. The straight line is a linear regression showing the trend of the data.

The experiment portrayed in Fig. 4-3 was conducted at a low rpm and the data illustrate a constant proportionality as expected from equation (4-5). When the drum rotational speed was increased the data exhibited a non-linear behaviour. Figure 4-4 is a plot of the experimental data for a case where the rpm was at 15. The data were fitted with a polynomial which shows the trend of the data.

As can be seen in Figure 4-4 the plot of $\ln (C_s-C_i)/(C_s-C)$, for the high rpm case, was not linear with time. This non-linearity could be attributed to three factors. One of

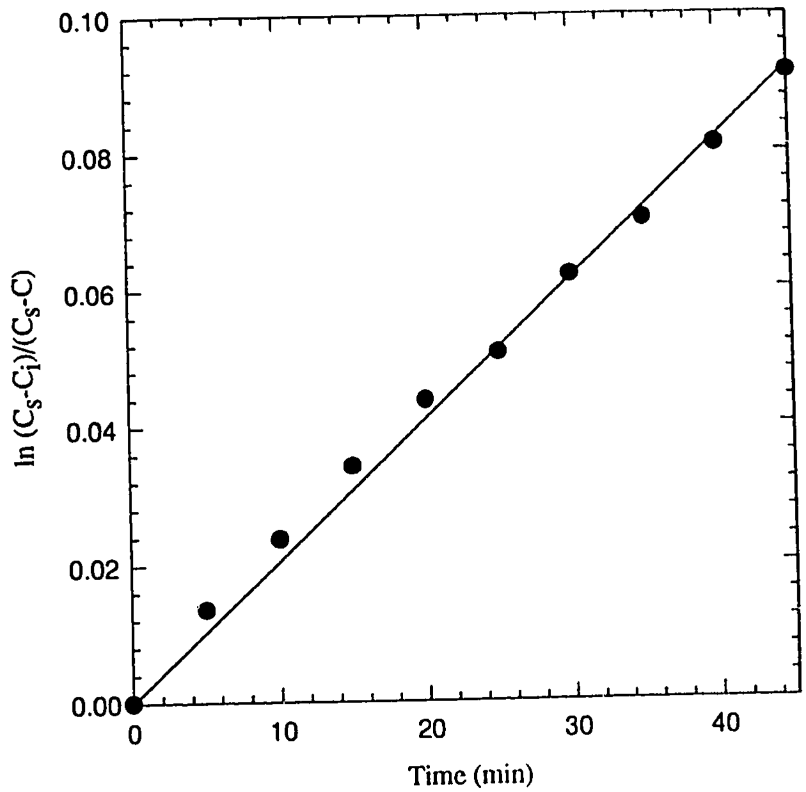

Figure 4-3. Plot of right-hand-side of equation (4-5) versus time for 2.9 RPM and α=0.43.

these is abrasion or erosion, when the sand particles erode or break up the β-naphthol particles thereby increasing the surface area of the particles. With reference to equation (4-4), an increase in the surface area of β-naphthol with time would increase the magnitude of the term on the right hand side. If the non-linearity of the plot was due to abrasion then the curvature of the plot would be concave upward not concave downward as shown in Fig. 4-4. A second possibility is if the β-naphthol particles are crystalline,

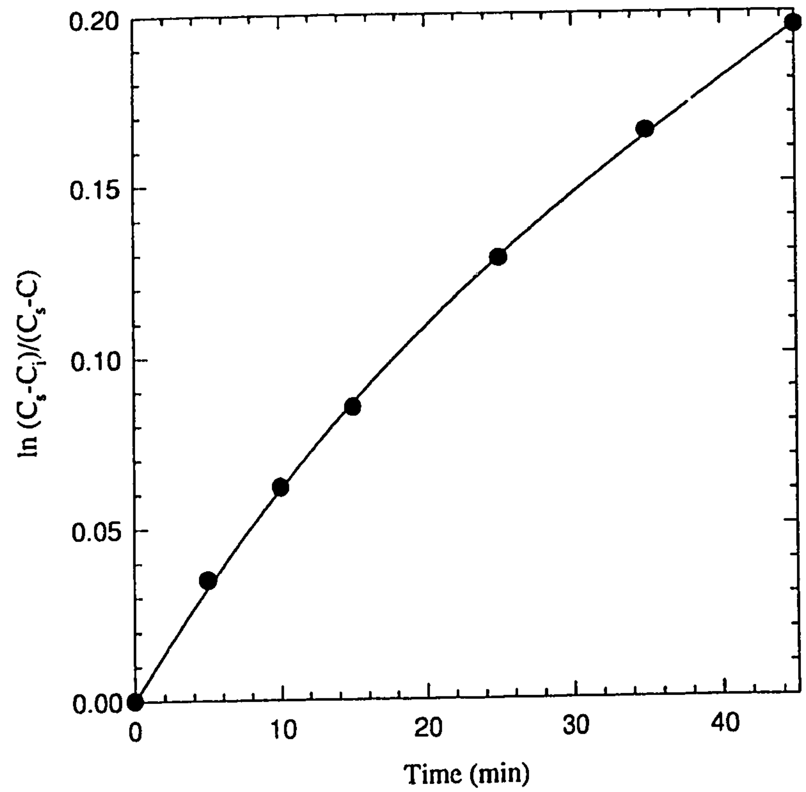

Figure 4-4. Plot of right-hand-side of equation (4-5) versus time for 15 RPM and α=0.43.

e.g. cube shaped, then the corners and the edges would dissolve faster then the face, which would give a rapid decrease in dissolution rate. The β-naphthol particles, however, were not crystalline. If a significant portion of the β-naphthol were dissolved during an experiment, then the surface area would decrease and the rate of dissolution would also decrease. Based on the mass of β-naphthol dissolved in the example experimental run, represented by Fig. 4-4, the surface area of the particles must have decreased by 67%.

Modified dissolution equations, taking into account this large decrease in the surface area due to the extensive dissolution in experiments at high rotational speeds, were developed.

4.3 Derivation of Governing Equations for Variable Particle Surface Area.

The following differential equation describes the rate of change of the solute mass:

$$\frac{dm}{dt} = -A\ k_s\ (C_s - C) \tag{4-6}$$

where m is the mass of β-naphthol particles in the drum. The surface area of the particles at time t is given by:

$$A = 4\ \pi\ r_p^2\ N_p \tag{4-7}$$

where r_p is the mean radius of the β-naphthol particles and N_p is the number of β-naphthol particles. The mass of solute in the drum at time t is given by:

$$m = 4/3\ \pi\ r_p^3\ \rho_p\ N_p \tag{4-8}$$

where ρ_p is the density of β-naphthol. Combining equations (4-7) and (4-8) gives the mass of solute, m, in terms of surface area, A.

$$m = 4/3\ \pi\ \rho_p\ N_p \left[\frac{A}{4\ \pi\ N_p}\right]^{3/2} = \frac{\rho_p\ A^{3/2}}{6\ \sqrt{\pi\ N_p}} \tag{4-9}$$

Differentiating equation (4-9) and equating it to equation (4-6), we obtain an expression for the change in surface area with time.

$$\frac{dA}{dt} = -\frac{4\sqrt{\pi N_p}}{\rho_p} A^{1/2} k_s (C_s - C) \tag{4-10}$$

To obtain an expression that describes the change in area with concentration (dA/dC) we can combine equations (4-10) and (4-4) to yield:

$$\frac{dA}{dC} = -\frac{4 V \sqrt{\pi N_p} (1 - \alpha)}{A^{1/2} \rho_p} \tag{4-11}$$

Integrating equation (4-11) and letting A_i and C_i be the initial area and concentration, respectively, we obtain the following equation which describes the change in surface area of the β-naphthol particles with the concentration changes in the liquid.

$$A = \left[A_i^{3/2} - \frac{6 \sqrt{\pi N_p} V (1 - \alpha) (C - C_i)}{\rho_p} \right]^{2/3} \tag{4-12}$$

Combining equations (4-4) and (4-12), yields equation (4-13), which can be used to calculate k_s, because this equation takes into effect the surface area change of the particles over time:

$$\frac{dC}{dt} = a_1 (a_2 - a_3 C)^{2/3} (C_s - C) \tag{4-13}$$

where:

$$a_1 = \frac{k_s}{V (1 - \alpha)} \tag{4-14}$$

$$a_2 = A_i^{3/2} + \frac{6\sqrt{\pi N_p}\ V\ (1 - \alpha)\ C_i}{\rho_p} \tag{4-15}$$

$$a_3 = \frac{6\sqrt{\pi N_p}\ V\ (1 - \alpha)}{\rho_p} \tag{4-16}$$

Rearranging equation (4-13), we obtain:

$$\frac{dC\ (1 - a_4\ C)^{-2/3}}{(C_s - C)} = a_1\ a_2^{2/3}\ dt \tag{4-17}$$

where $a_4 = a_3/a_2$. An approximate solution to equation (4-17) can be obtained by expanding the $(1 - a_4C)^{-2/3}$ term using binomial series expansion. Using the first three terms of the expansion, and integrating from C_i to C and t_i to t, we obtain:

$$\int_{C_i}^{C} \frac{dC}{(C_s - C)} + 2/3\ a_4 \int_{C_i}^{C} \frac{C\ dC}{(C_s - C)} + 5/9\ a_4^2 \int_{C_i}^{C} \frac{C^2\ dC}{(C_s - C)} = a_1\ a_2^{2/3} \int_{t_i}^{t} dt \tag{4-18}$$

The solution to equation (4-18) has the form:

$$y_1 + y_2 + y_3 = a_1\ a_2^{2/3}\ t \tag{4-19}$$

where:

$$y_1 = \ln\left[\frac{C_s - C_i}{C_s - C}\right] \tag{4-20}$$

$$y_2 = 2/3\ a_4 \left(C_i - C - C_s \ln \left[\frac{C_s - C}{C_s - C_i} \right] \right) \tag{4-21}$$

$$y_3 = -5/9\ a_4^2 \left(C\ (C_s + 1/2C) - C_i\ (C_s + 1/2C_i) + C_s^2 \ln \left[\frac{C_s - C}{C_s - C_i} \right] \right) \tag{4-22}$$

Figure 4-5 is a plot of the concentration terms (y_i) from equation (4-19) as a function of time. The first set of data (curve y_1) is fitted with a second order regression, and the last two sets of data (y_2 and y_3) are fitted with straight lines.

The lowest curve (y_1) is the same as Fig. 4-4 and it represents the zeroth order solution of equation (4-17). Curves (y_1+y_2) and (y_1+y_2+y_3) represent the first and second order solutions of equation (4-17), respectively. As can be seen from Fig. 4-5, the second order solution represents the best solution to equation (4-17). The slope of the line (y_1+y_2+y_3) is equal to $a_1 a_2^{2/3}$, and we have:

$$k_s = \frac{\text{slope}\ V\ (1 - \alpha)}{a_2^{2/3}} \tag{4-23}$$

For this case, k_s is equal to 4.4×10^{-5}. As the second order solution gave a linear fit to the data, i.e. constant mass transfer coefficient, the full form of equation (4-19) was used to analyze the experimental data.

In the series of experiments, three parameters were changed: drum rotational speed, slurry holdup, and solids volume fraction. When one parameter was changed, the other

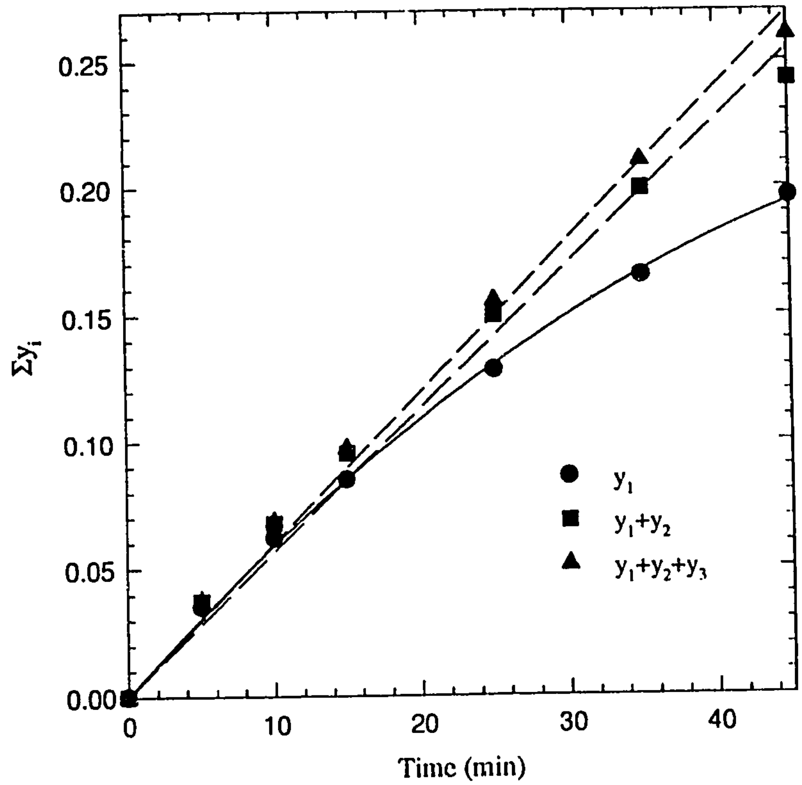

Figure 4-5. Plot of concentration functions from equation (4-19) versus time for 15 RPM and α=0.43.

two were kept constant. Each experimental run for the slurry holdup and solids volume fraction was repeated to check for reproducibility in evaluating k_s. For all experiments (drum rotational speed, slurry holdup, and solids volume fraction), the small drum was used. The drum was 0.30 m in length and 0.29 m in diameter. The complete results can be found in Appendix A.

4.4 Dependence of Mass Transfer Coefficient (k_s) on Drum Rotational Speed.

The drum rotational speed was varied from 0.33 to 15 rpm, and the solid-liquid mass transfer coefficient, k_s, was calculated for each run using equation (4-19). For each run in this set of experiments, the slurry holdup and solids volume fraction were held constant at 8.7 % and 0.43, respectively. Figure 4-6 shows the variation of k_s as a function of the drum rotational speed. The data were fitted with a polynomial which shows the trend of the data.

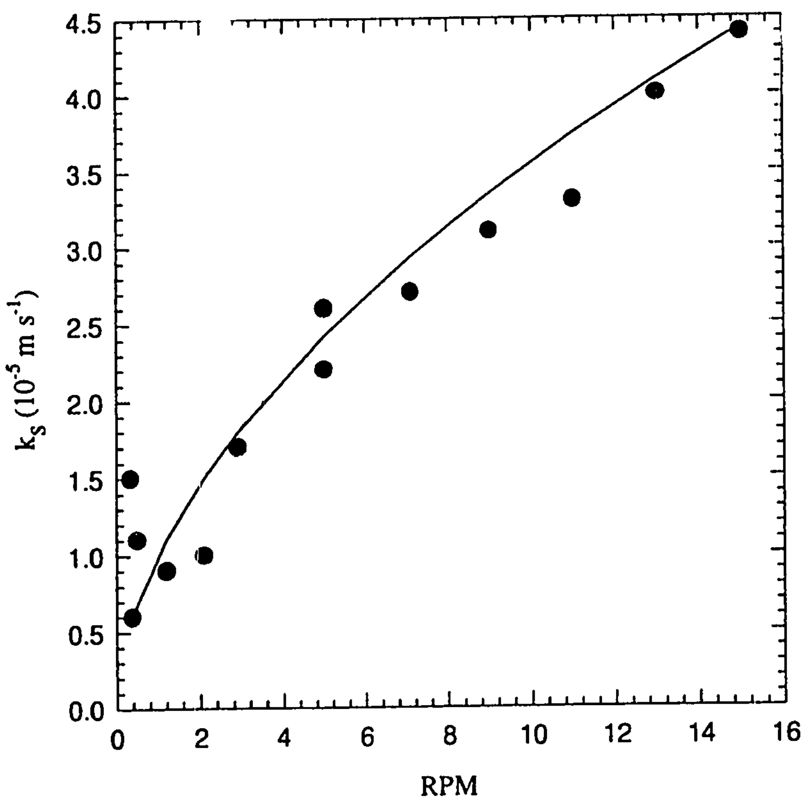

Figure 4-6. Variation of k_s with rpm for a slurry holdup of 8.7 % and α=0.43.

At the lowest rpm the least value of the mass transfer coefficient was 5.7×10^{-6} m s^{-1} and at the upper range of rpm (15 rpm) the mass transfer coefficient was 4.4×10^{-5} m s^{-1}. Repeat experiments were performed at the high rpm (15 rpm), the low rpm (0.33 rpm) and at 5 rpm to check for reproducibility. The variation in the mass transfer coefficient was 1.6 % at 15 rpm, 62 % at 0.33 rpm, and 17 % at 5 rpm. The large variation of the mass transfer coefficient at low rpm cannot be explained through observation of the slurry motion in the drum during the experiment.

As can be seen from Fig. 4-6, above 2 rpm, there is an increase in the mass transfer coefficient with increasing rpm. This trend was caused by the increased mixing of the β-naphthol particles in the sand-water slurry as rpm was increased.

The maximum rpm used in this study was well below the critical rpm value. The critical rpm occurs when the centrifugal force acting on the particles equals the gravitational force at the critical value and the particles are pushed to the outer wall. Perry et al. (1984) gives an appropriate equation for critical rpm in ball-mills:

$$N_{cr} = \frac{42.3}{\sqrt{D}} \qquad (4\text{-}24)$$

where N_{cr} is the critical rpm and D is the diameter of the drum, m. The drum's critical rpm is 78 rpm. It is well above the maximum rpm value of 15 used in this set of experiments.

4.5 Dependence of Mass Transfer Coefficient (k_s) on Slurry Holdup.

Slurry holdup is defined as the volume of slurry (which consists of sand, β-naphthol, and water) divided by the volume of the empty drum. This ratio can also be called the slurry volume fraction, as we are dealing with a batch system, but the term slurry holdup is used more commonly, and we shall adopt it here. The slurry holdup was varied from 4.4 % to 17 %. For each run in this set of experiments the drum rotational speed was held constant at 3 rpm and the solids volume fraction in the slurry was set at 0.43. Figure 4-7 shows the variation of k_s as a function of slurry holdup. The lines in the plot are simple linear regressions showing the trend of the data.

At a slurry holdup of 4.4 % the mass transfer coefficient was 8.0×10^{-6} m s^{-1}, while at a slurry holdup of 17 %, the coefficient was found to be 2.0×10^{-5} m s^{-1}. Each experiment was repeated once. The largest variation in the reproducibility of the mass transfer coefficient, for this set of experiments, occurred at a slurry holdup of 11 % with the variation being 15 %. The minimum variation of 1.6 % occurred at a slurry holdup of 8.8 %.

The range of slurry holdup that was varied covers two different types of slurry motion in the rotary drum. At low slurry holdup (slurry holdup of 4.4 % and 6.6 %) the sand remained on the baffles throughout an entire revolution of the drum. At higher slurry holdup (greater than 6.6 %) the increase in the amount of sand on each baffle caused the sand to fall off of each baffle at the top of the rotation, as shown in Fig. 4-2.

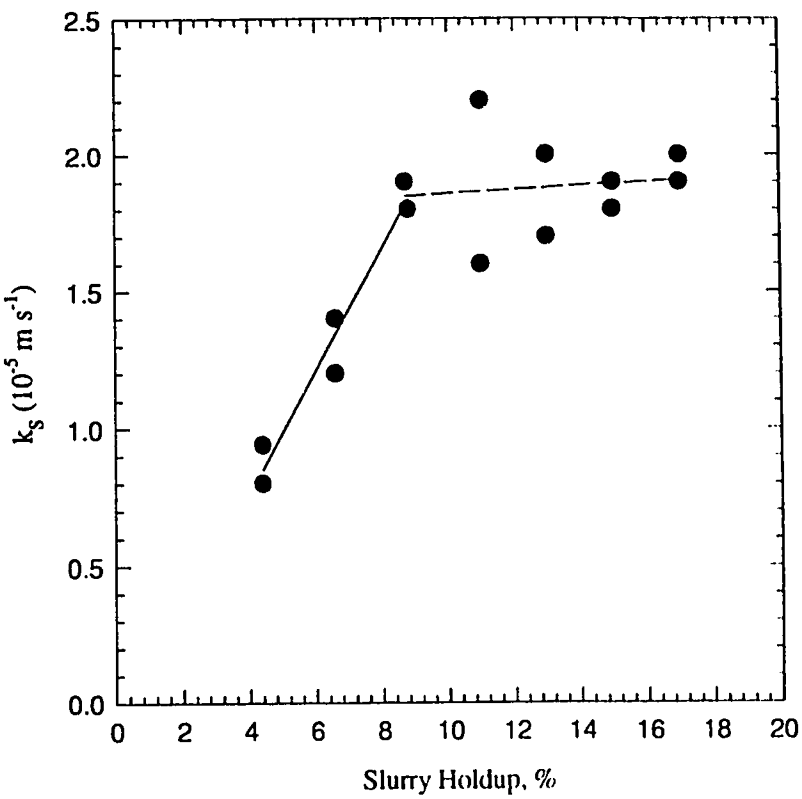

Figure 4-7. Variation of k_s with slurry holdup for 3 RPM and α=0.43.

This increased motion increased the amount of slurry that was actively mixed in the bottom of the drum, giving a higher mass transfer coefficient. This change in slurry motion gave a discontinuity in the dependence of k_s on slurry holdup, as indicated by the lines in Fig. 4-7. For values of slurry holdup above 8 %, k_s was constant within experimental variability.

4.6 Dependence of Mass Transfer Coefficient (k_s) on Solids Volume Fraction.

Solids volume fraction was defined as the ratio of the volume of sand to the total slurry volume. Letting α be the solids volume fraction, we have $\alpha = V_s / (V_s + V_L)$, where V_s is the volume of the sand and V_L is the volume of the liquid. Figure 4-8 shows the variation of k_s with solids volume fraction. Both lines in Fig. 4-8 are simple linear regressions showing the trend of each different type of mixing.

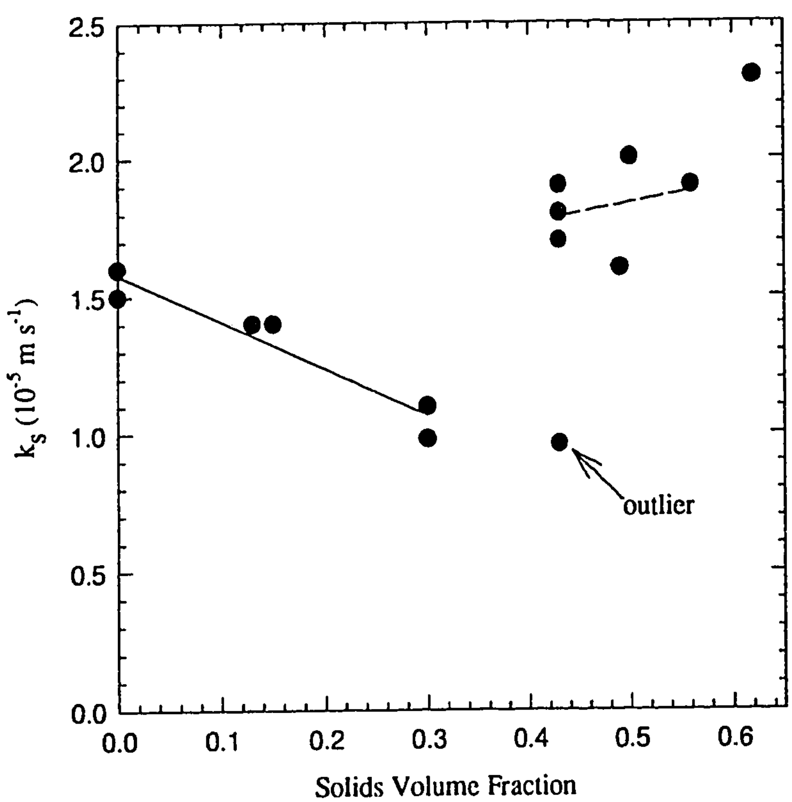

Figure 4-8. Variation of k_s with solids volume fraction for 3 RPM and a slurry holdup of 8.7 %.

The solids volume fraction was varied from 0 to 0.62, giving values of k_s ranging from 1.5 x 10^{-5} m s^{-1} to 2.3 x 10^{-5} m s^{-1}, respectively. Again the drum rotational speed was held at 3 rpm and the slurry holdup remained at 8.7 %, throughout this set of experiments. At a solids volume fraction of 0.30 the mass transfer coefficient was at a minimum value of 9.7 x 10^{-6} m s^{-1}. Each experiment in the solids volume fraction set of experiments was reproduced with the smallest variation being 1.7 % at a solids volume fraction of 0.15. The largest variation of 47 %, occurred at a solids volume fraction of 0.43, but there were 5 experimental runs conducted at this base case (R.P.M. of 3, slurry holdup of 8.5 %, and a solids volume fraction of 0.43). Since the lowest point was outside the standard error for these 5 data points (the average is 1.6 x 10^{-5} with a standard error of 1.7 x 10^{-6}) the low point in this series was discarded as an outlier.

As in the slurry holdup set of experiments, there were two different ways in which the slurry was mixed in the rotary drum. At solids volume fractions of 0, 0.15 and 0.30, all of the sand and β-naphthol particles remained on the baffles throughout the drum rotation, which gave a decrease in mixing of slurry solids and consequently a lower mass transfer coefficient. This range of solid volume fraction (solids volume fraction of 0 to 0.30) comprises the first type of slurry mixing. In the higher range of solids volume fraction (runs at an α of 0.43, 0.50, 0.56 and 0.62) the solids (sand and β-naphthol) did not stay on the baffles but was mixed at the bottom of the drum during each rotation, as shown in Fig. 4-2. Consequently, this increased mixing gave an increase in the mass transfer coefficient, k_s, relative to the experiments at α=0.15 and α=0.30. In the range of solids volume fraction from 0.43 to 0.56, the mass transfer coefficient was independent of solids volume fraction. The data point at α=0.62 may suggest an increase in k_s with α, but this experiment had so little liquid in the slurry that sampling was erratic, and concentrations fluctuated with time. Consequently, this measurement had a considerable level of uncertainty and does not provide a strong argument for a trend of k_s with solids volume fraction in this range.

Another reason for the increase in the mass transfer coefficient at solids volume fractions above 0.30 could be due to grinding of the β-naphthol by the sand particles, either by attrition or erosion. Attrition is the breaking up of the β-naphthol particles through the action of the sand particles while erosion is the wearing down of the β-naphthol particles from the sand particles hitting or scraping them during mixing in the drum. However, in both cases of grinding there would be an increase in the surface area of the β-naphthol particles due to the active formation of very fine solids. The plot of the data in Fig. 4-4 would be concave upwards because of this possible increase in area. Since the plot is concave down for this typical run at high rpm, the increase in k_s in Fig. 4-8 cannot be attributed to grinding.

4.7 Experiments with the Large Drum.

For correlation and scale-up purposes, a comparison is needed between the small drum and a larger drum. The larger drum was made of steel with a diameter of 0.58 m and a length of 0.90 m. The experiments that were conducted in the small drum (i.e.

varying rpm, slurry holdup, and solids volume fraction) were attempted in the larger drum, but difficulties were encountered during these experiments and most of the runs could not be successfully completed. The large drum tended to slip on the rollers, because there was not proper contact between the drum and the rollers. Table 4-1 shows the results of the successful experimental runs only. Since the drum was made of steel, the motion of the slurry inside the drum could not be observed.

The values in Table 4-1 will be used in the correlation that will be conducted in the next section. The terms LDRPM and LDSH stand for large drum rpm varying experiment and large drum slurry holdup varying experiment, respectively.

Table 4-1. Solid-Liquid Mass Transfer Coefficient Results

for the Large Drum Experiments.

Run	RPM	Slurry Holdup, %	Solids Volume Fraction, α	k_s, (10^{-5} m s^{-1})
LDRPM	3.7	8.9	0.43	3.9
LDSH	0.73	4.4	0.43	2.8

4.8 Correlation of the Mass Transfer Coefficient.

So far there have been four different expressions defined for Froude number, they are:

$$Fr_1 = N^2 \frac{D}{g} \tag{4-25}$$

$$Fr_2 = \frac{V_\omega}{\sqrt{g\ h}} \tag{4-26}$$

$$Fr_3 = \frac{V_\omega}{\sqrt{g\ D\ (S_s - 1)}} \tag{4-27}$$

$$Fr_4 = \frac{V_\omega}{\sqrt{2\ g\ h\ (S_s - 1)}} \tag{4-28}$$

Fr_1 and Fr_3 are based on drum diameter, whereas Fr_2 and Fr_4 are based on the height of the slurry in the drum, h. Fr_1 and Fr_3 can be used when the slurry is being completely mixed in the drum, as shown in Fig. 4-2. Fr_2 and Fr_4 can be used when slurry motion in the rotary drum behaves as a liquid or slurry flowing over a weir, as shown in Fig. 4-1, for low rotational speeds. The plots of Fig. 4-7 and Fig. 4-8 indicate that when the slurry is being completely mixed (i.e. no sand staying on the baffles throughout a rotation of the drum) then the mass transfer coefficient, k_s, is not dependent on slurry holdup or solids volume fraction. Therefore, the Froude expression that is not dependent upon the slurry height, h, can be used in the correlation of the data.

Many mass transfer studies use a combination of dimensionless numbers (Reynolds, Sherwood, and Schmidt) to correlate the data. A definition of Schmidt number is as follows:

$$Sc = \frac{\mu_{mix}}{\rho_{mix} D_{mix}} \tag{4-29}$$

with ρ_{mix}, μ_{mix} and D_{mix} are defined as:

$$\rho_{mix} = \alpha \rho_s + (1 - \alpha) \rho_w \tag{4-30}$$

$$\frac{\mu_{mix}}{\mu_w} = \exp\left[2.66 \frac{\alpha}{1 - \alpha}\right] \tag{4-31}$$

$$\frac{D_{mix}}{D_{aqu}} = 1 - \alpha^{2/3} \tag{4-32}$$

where ρ_s and ρ_w are the densities of sand and water, respectively, μ_w is the viscosity of water, α is the solids volume fraction, and D_{aqu} is the diffusivity of β-naphthol in water. Equation (4-31) was obtained from Barnea & Mizrahi (1973) and equation (4-32) was obtained from Duplessis and Masliyah (1991).

However, the data from the present study show a weak dependence on Schmidt number. For example the mass transfer coefficient, k_s, at a solids volume fraction of 0 is very close to the mass transfer coefficient at a solids volume fraction of 0.43 (1.6×10^{-5} m s^{-1} and 1.8×10^{-5} m s^{-1}, respectively). The Schmidt numbers over this range of solids volume fraction varies from 984 at a solids volume fraction of 0 to 9950 at a solids volume fraction of 0.43. Therefore a simple correlation using just Froude number can be used to correlate the data from the present study. The data used in the correlation include: the complete range of drum rotational speed, slurry holdup from 8.8 % to 17 %, solids volume fraction from 0.43 to 0.56, and both experiments done in the large drum. A plot of the variation of Sherwood number with Fr_3 is shown in Fig. 4-9.

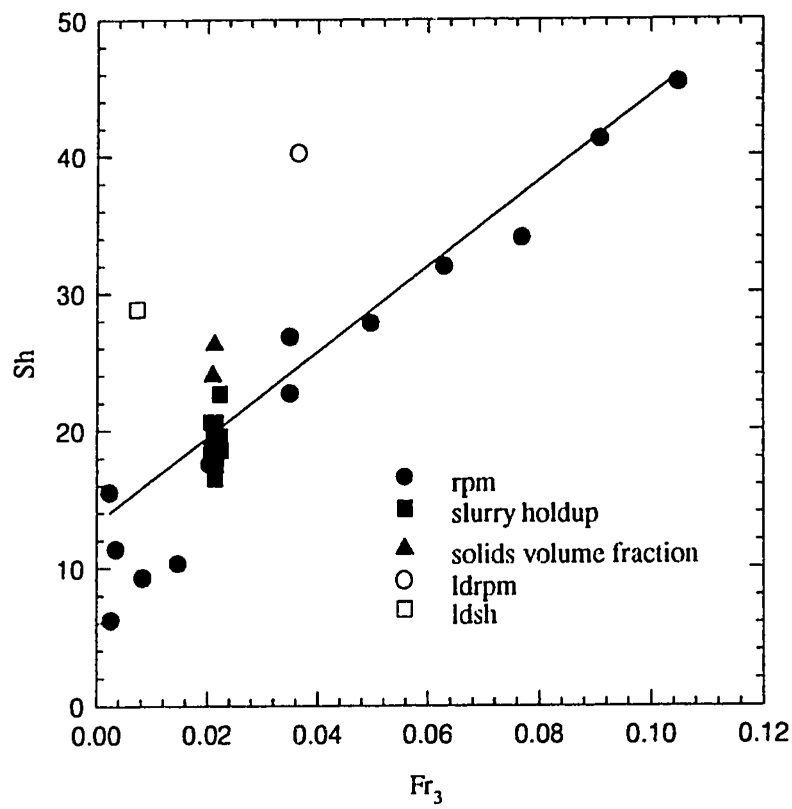

Figure 4-9. Variation of Sherwood number with Froude Number (Fr_3).

Where Sherwood number is defined as:

$$Sh = \frac{k_s \, D_p}{D_{mix}} \qquad (4\text{-}33)$$

where D_p is the particle diameter.

Figure 4-9 shows that the expression Fr_3 correlates the data fairly well, except for the two experiments completed in the large drum. The large drum was stainless steel, so the motion of the slurry inside the large drum could not be observed. There may have been increased mixing in the large drum which would have resulted in unexpectedly high values of k_s. The reason for the increase in mixing in the large drum could be due to the motion of the slurry on the baffles. In the small drum at low rpm, the slurry tended to stick on the baffles, giving limited mixing. At the larger scale, this tendency may have been reduced, so that more of the slurry was mixed at the bottom of the drum, resulting in an unexpectedly high values of k_s. If this hypothesis is correct, then the data from the small drum are conservative in predicting the mass transfer coefficient after scale-up. Further experiments with a drum having a diameter of 0.5 m would be required to confirm this mechanism.

4.9 Comparison with Results of Miwa et al. (1991).

Miwa et al. (1991) used the Froude number to correlate mass transfer coefficient for the cementation of cuprous ion aqueous solution by iron particles. Their Froude number was defined as:

$$Fr_t = N^2 \frac{D}{g} \tag{4-34}$$

where N is rotational rate of the drum (s^{-1}), D is the diameter of the drum and g is the gravitational constant. The equations used by Miwa et al. to calculate k_L', equations (2-5) to (2-11), were used to calculate k_L' for the data from the present study. Here, only the set of data where rpm was varied was used in the calculations. For the expression of k_La, equation (2-6), we have set ψ_i and β_i equal to unity, because the β-naphthol particles were observed to be roughly spherical.

Figure 4-10 shows the data of Miwa et al. and the data from the present study as a function of rpm. All the data shown on the plot were used to obtain the linear regression line, which shows the overall trend of the data.

As shown in the plot of Fig. 4-10 the present study extends the results of Miwa et al. to a lower Froude number range. The range of Froude number, for the present study, was much lower than Miwa et al. due to the much lower rotational velocity of the drum. There was a maximum in k_L' in the upper range of Froude number for Miwa et al. results because they operated above the critical rpm for all three drums used in their study.

The rotational speed in the present study, however, remained well below the critical value, as stated earlier. There is substantial concordance between the present

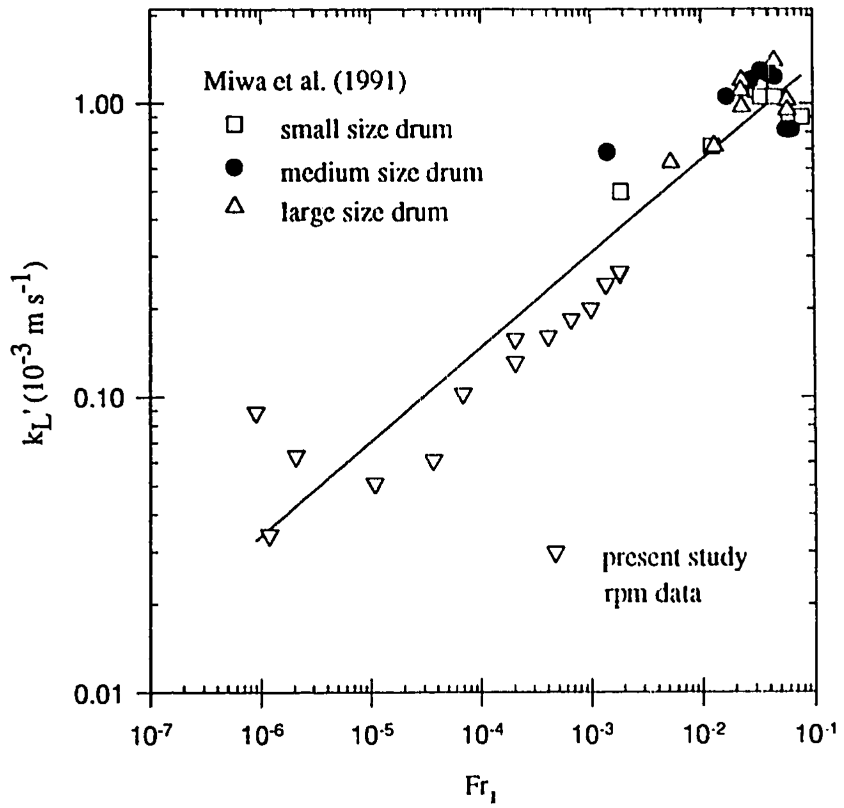

Figure 4-10. Variation of k_L' with Froude number (Fr_l).

Present study and Miwa et al. results.

study and that of Miwa et al., even though they used different size drums and different particle sizes from the present study. In their experiments they used three different size drums. The small drum was 0.168 m in diameter, 0.41 m long, and had a volume of 10 L; the medium size drum was 0.26 m in diameter, 0.30 m long, and had a volume of 16 L; while the largest drum was 0.484 m in diameter, 0.98 m long and had a volume of 200 L. They also used four different particle sizes for the iron particles. These were 1.0 x

10^{-4}; 1 x 10^{-3}; 5 x 10^{-3}; and 1.0 x 10^{-2} m in diameter. The drum size in the present study was 0.29 m in diameter, 0.30 m in length, and 20 L in volume and the particle size of the β-naphthol was 4.62 x 10^{-4} m.

5.0 CONCLUSIONS.

1. The effect of drum rotational speed on the solid-liquid mass transfer coefficient, k_s, was studied over the range from 0.33 to 15 rpm. The mass transfer coefficient, k_s, varied from a low of 5.7×10^{-6} m s^{-1} at 0.33 rpm to a high of 4.4×10^{-5} m s^{-1} at 15 rpm. There was an increase in the mass transfer coefficient as the drum rotational speed increased. During the experimental runs the rpm remained well below the critical value of 78 rpm.

2. There are two types of slurry motion observed in the small drum during the experiments. One type of mixing is comparable to that of a liquid flowing over a weir. The drum rotational speed controls the frequency of weirs or baffles. The solids (β-naphthol and sand) remain on the baffle throughout a rotation of the drum. This type of mixing occurred at low slurry holdup (less than 8.7 %) and low solids volume fraction (less than 0.43). A second type of mixing involves the slurry dropping off the baffles and mixing in the bottom of the drum. This type of mixing occurred during the drum rotational speed varying set of experiments and at high slurry holdup (at 8.7 % and higher) and high solids volume fraction (at 0.43 and higher).

3. Slurry holdup was varied from 4.4 % to 17 % to see how it affected the mass transfer coefficient, k_s. At low values of slurry holdup, e.g. 4.4 %, the mass transfer coefficient was 8.0×10^{-6} m s^{-1}, and at the higher range of slurry holdup, e.g. 17 %, the mass transfer coefficient was 2.0×10^{-5} m s^{-1}. In the range (slurry holdup less than 8.7 %) where the solids remained on the baffles, the mass transfer coefficient increased linearly with

increasing slurry holdup. Above 8.7 % slurry holdup the mass transfer coefficient was not dependent upon increasing slurry holdup.

4. The effect of solids volume fraction on the mass transfer coefficient, k_s, was also studied. The solids volume fraction was varied from 0 to 0.62. The mass transfer coefficient at zero solids, i.e. no sand, was 1.5×10^{-5} m s^{-1}. It then decreased to 9.7×10^{-6} m s^{-1} at a solids volume fraction of 0.30, and then increased to 2.3×10^{-5} m s^{-1} at 0.62 solids volume fraction. The decrease in the mass transfer coefficient in the lower range of the solids volume fraction [illegible]) was attributed to less mixing of the slurry in the drum. In this lower range of [illegible] volume fraction, some of the sand and β-naphthol remained on the baffles throughout the drum rotation. This resulted in a decrease in mixing and consequently a lower mass transfer coefficient. However, at the higher range of solids volume fraction (0.43 to 0.62), less solids (sand and β-naphthol) stayed on the baffles. Consequently, there was greater mixing of the slurry and an increase in the mass transfer coefficient, k_s.

5. The effects that the above parameters, (drum rotational speed, slurry holdup, and solids volume fraction), had on the solid-liquid mass transfer coefficient, k_s, were correlated for use in scale-up operations. The equation used to correlate this data is:

$$Fr_3 = \frac{V_\omega}{\sqrt{g\ D\ (S_s - 1)}} \tag{5-1}$$

The data that was used in this correlation include all the data from the drum rotational speed varying set of experiments, slurry holdup of 8.7% and greater, solids volume fraction from 0.43 to 0.56, and both experiments done in the large drum.

6. A comparison of results was done between the present study and Miwa et al. (1991). The equations used by Miwa et al. to calculate k_L' were used to calculate k_L' for the rpm varying set of data from the present study. There was good agreement between the present study and that of Miwa et al., even though they used different size drums and different particle sizes from the present study. The present study extends the results of Miwa et al. to the lower ranges of Froude number.

6.0 RECOMMENDATIONS.

1. The experimental runs done in the large drum concur substantially with the Froude number, except for the experiments done in the large drum. The result of these experimental runs were higher than predicted from the correlation. No observations could be made while the slurry was mixing in the large drum, as the large drum was made of steel. There may have been increased mixing in the large drum. This effect could be the reason that the mass transfer coefficient is higher in the large drum. Further experiments should be conducted to investigate this effect.

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APPENDIX A

This appendix contains the raw data and calculations for the zeroth order solution for the mass transfer coefficient, k_s. A sample calculation is also given to show how to obtain the second order solution for the mass transfer coefficient, k_s.

Drum Rotational Speed Varying Set of Data

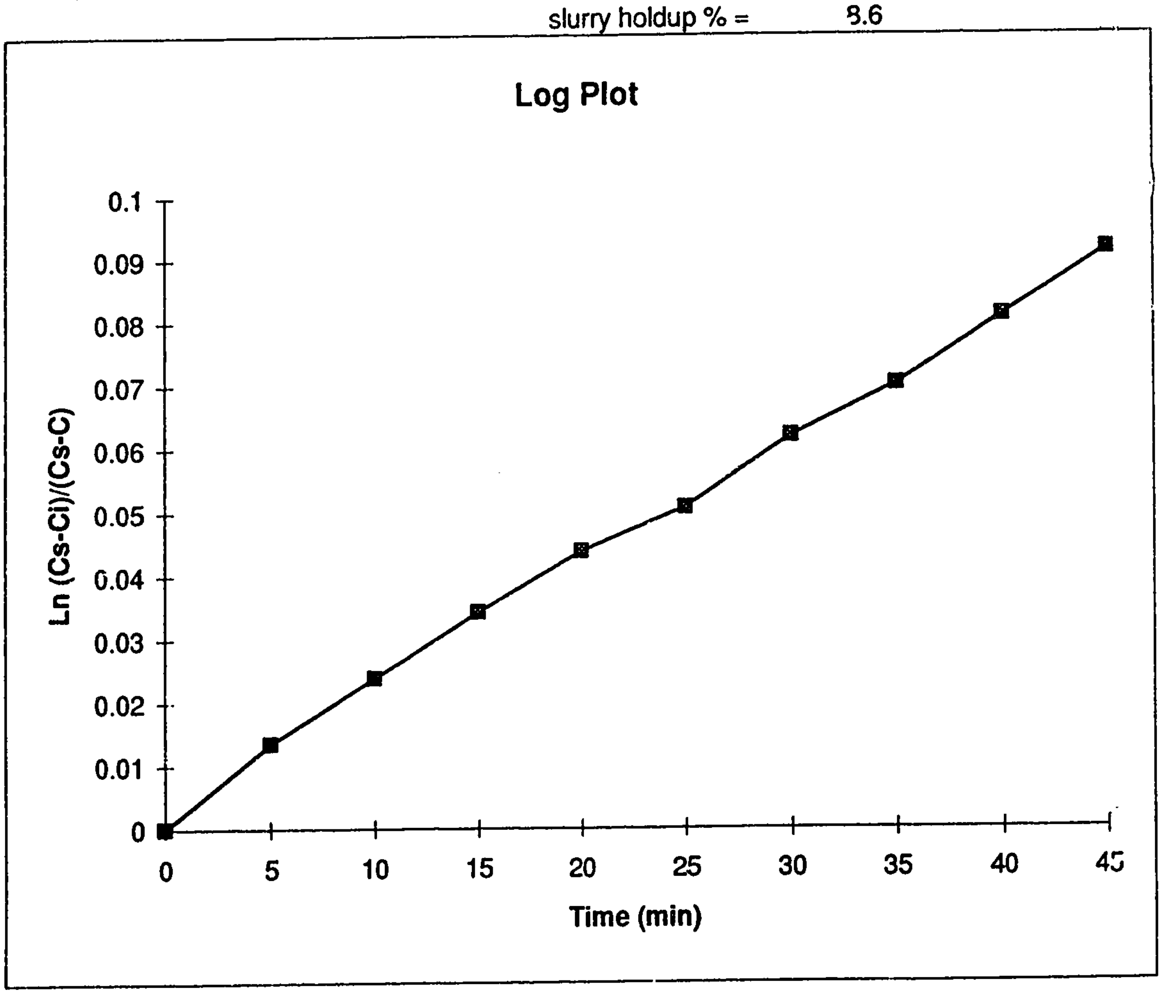
RUN 1	Aug 25/93	Sand and	Naphthol			
R.P.M.	2.9	Size	425-500 microns			
Cs (g/l)	0.74	4 Baffles				
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)	Regression	
1	0	0.106	0.0111	0	0.002152	0
2	5	0.202	0.0209	0.0135	6.23E-05	#N/A
3	10	0.274	0.0282	0.0237	0.985249	0.002311
4	15	0.347	0.0356	0.0342	333.9489	5
5	20	0.413	0.0423	0.0437	0.001783	2.67E-05
6	25	0.460	0.0471	0.0507		
7	30	0.538	0.0549	0.0620	Only the first 25 minutes of exp.,	
8	35	0.593	0.0605	0.0702	is analyzed in regression	
9	40	0.665	0.067[illegible]	0.0810		
10	45	0.733	0.074[illegible]	0.0914		

Sand	2002.90 g	Surface Area	2.18E-03 m2
Water	1006.57 g	Liquid Volume	1.01E-03 m3
Naphthol	0.2043 g	Solid Volume	7.56E-04 m3
Sand and water pre-mixed for 20 minutes		Total Volume	1.76E-03 m3

Ks = 1.66E-05 m/s

svf = 0.43

slurry holdup % = 8.6



Drum Rotational Speed Varying Set of Data

RUN 2 Aug 27/93 Sand and Naphthol

R.P.M. 4.97 Size 425-500 microns

Cs (g/l) 0.74 4 Baffles

Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)		Regression	
1	0	0.104	0.0109	0		0.003053	0
2	5	0.215	0.0222	0.0156		4.52E-05	#N/A
3	10	0.327	0.0335	0.0315		0.996425	0.001678
4	15	0.445	0.0456	0.0488		1393.665	5
5	20	0.527	0.0539	0.0608		0.003924	1.41E-05
6	25	0.618	0.0631	0.0743			
7	30	0.716	0.0731	0.0892	Only the first 25 minutes of exp.,		
8	35	0.791	0.0807	0.1006	is analyzed in regression		
9	40	0.875	0.0892	0.1136			
10	45	0.939	0.0958	0.1238			

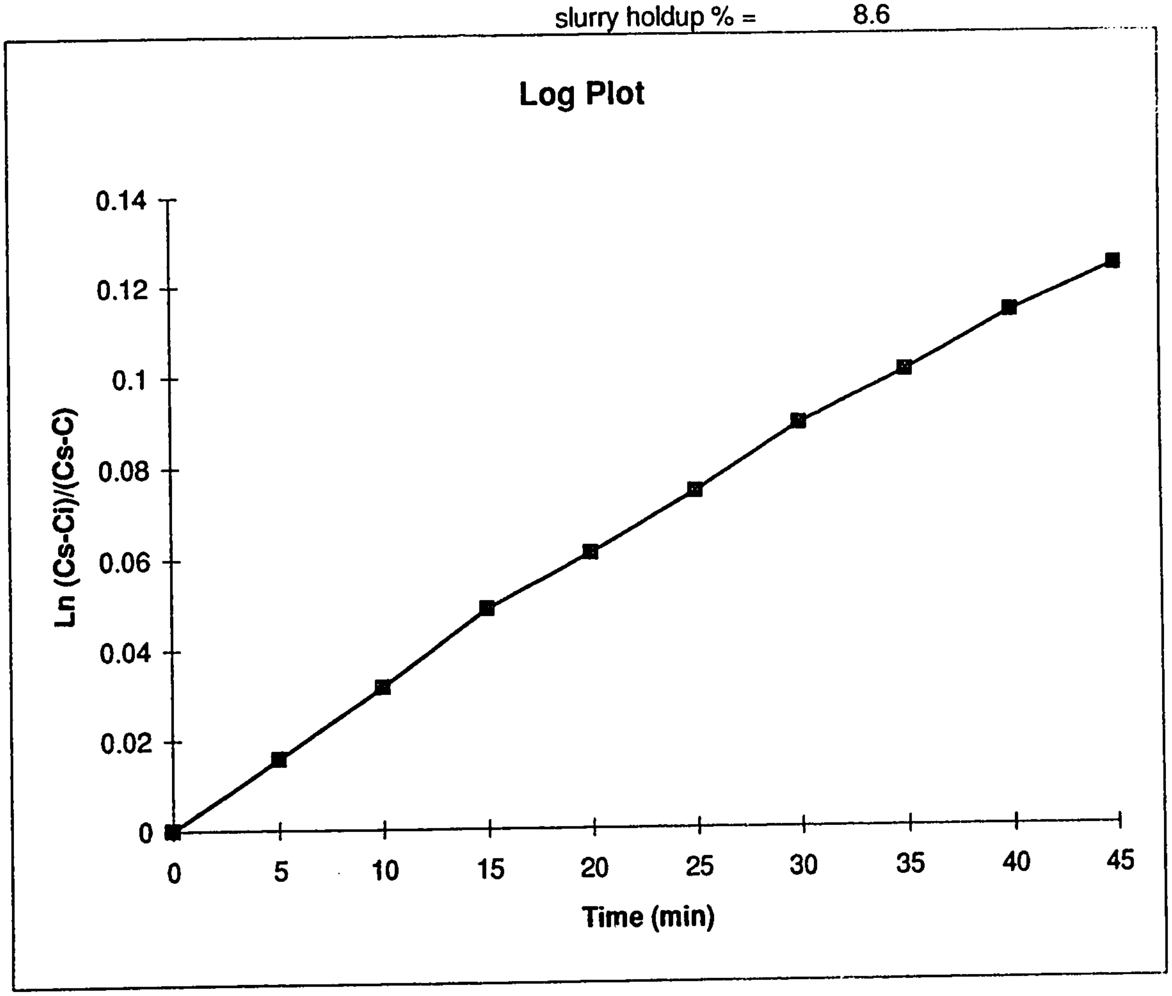
Sand	2001.41 g	Surface Area	2.21E-03 m2
Water	1008.64 g	Liquid Volume	1.01E-03 m3
Naphthol	0.2073 g	Solid Volume	7.55E-04 m3
		Total Volume	1.77E-03 m3

Sand and water pre-mixed for 25 minutes

Ks = 2.33E-05 m/s

svf = 0.43

slurry holdup % = 8.6



Drum Rotational Speed Varying Set of Data

RUN 3	Aug 31/93	Sand and	Naphthol		
R.P.M.	4.99	Size	425-500 microns		
Cs (g/l)	0.74	4 Baffles			
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)	
1	0	0.115	0.0120	0	
2	5	0.208	0.0214	0.0130	
3	10	0.286	0.0294	0.0242	
4	15	0.375	0.0384	0.0369	
5	20	0.474	0.0484	0.0513	
6	25	0.575	0.0588	0.0664	
7	30	0.648	0.0662	0.0774	
8	35	0.710	0.0725	0.0868	
9	40	0.791	0.0807	0.0991	
10	45	0.882	0.0899	0.1132	

Regression	
0.00258	0
3.73E-05	#N/A
0.996837	0.001384
1575.946	5
0.00302	9.58E-06

Only the first 25 minutes of exp., is analyzed in regression

Sand	2000.78 g
Water	1002.75 g
Naphthol	0.2036 g

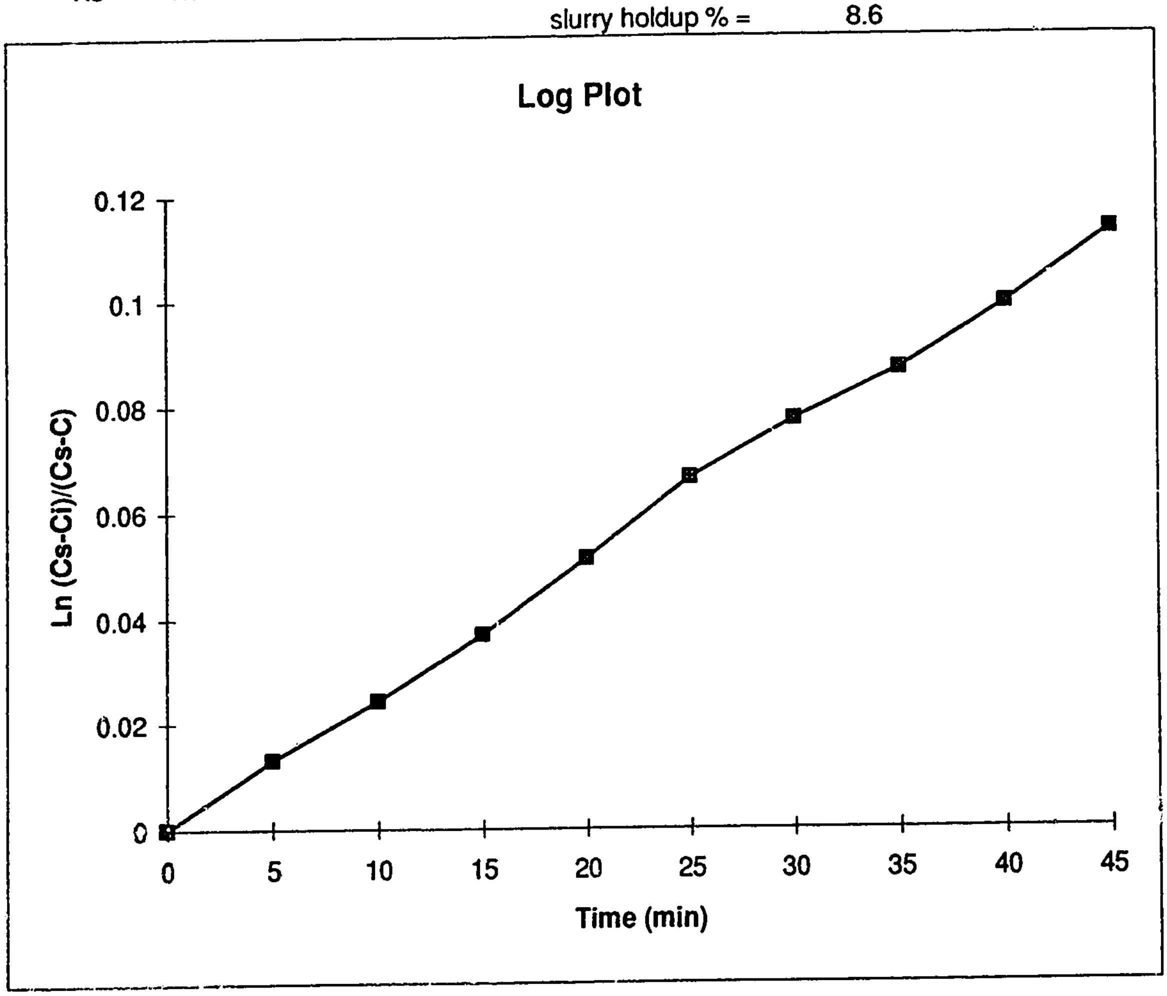
Sand and water pre-mixed for 20 minutes

Suface Area	2.17E-03 m2
Liquid Volume	1.00E-03 m3
Solid Volume	7.55E-04 m3
Total Volume	1.76E-03 m3

Ks = 1.99E-05 m/s

svf = 0.4291

slurry holdup % = 8.6



Drum Rotational Speed Varying Set of Data

RUN 4	Sept 17/93	Sand and	Naphthol			
R.P.M.	7.06	Size	425-500 microns			
Cs (g/l)	0.74	4 Baffles				
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)	Regression	
1	0	0.053	0.0057	0	0.003405	0
2	5	0.209	0.0216	0.0219	0.000112	#N/A
3	10	0.323	0.0332	0.0382	0.987282	0.003495
4	15	0.416	0.0425	0.0514	310.5033	4
5	25	0.624	0.0637	0.0823	0.003793	4.89E-05
6	35	0.806	0.0822	0.1100		
7	45	0.949	0.0967	0.1323	Only the first 25 minutes of exp., is analyzed in regression	

Sand	2000.89	g
Water	1004.31	g
Naphthol	0.2019	g

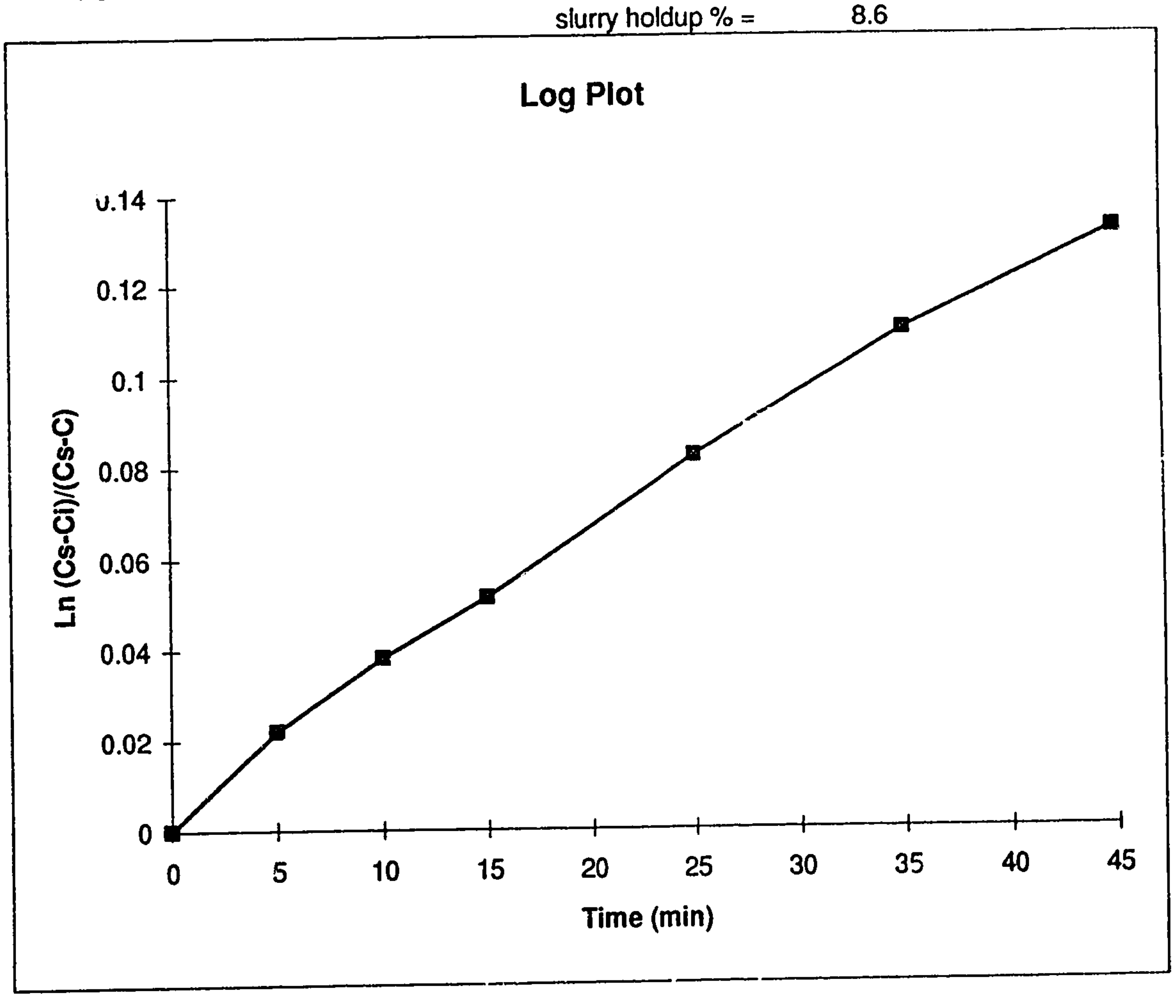
Sand and water pre-mixed for 10 minutes

Surface Area	2.15E-03	m2
Liquid Volume	1.01E-03	m3
Solid Volume	7.55E-04	m3
Total Volume	1.76E-03	m3

Ks = 2.65E-05 m/s

svf = 0.43

slurry holdup % = 8.6



Drum Rotational Speed Varying Set of Data

RUN 5	Sept 20/93	Sand and	Naphthol			
R.P.M.	8.98	Size	425-500 microns			
Cs (g/l)	0.74	4 Baffles				
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)	Regression	
1	0	0.051	0.0055	0	0.003698	0
2	5	0.206	0.0213	0.0217	7.91E-05	#N/A
3	10	0.332	0.0341	0.0397	0.994806	0.002471
4	15	0.447	0.0458	0.0564	766.1002	4
5	25	0.674	0.0688	0.0901	0.004678	2.44E-05
6	35	0.872	0.0889	0.1205		
7	45	1.055	0.1075	0.1495	Only the first 25 minutes of exp., is analyzed in regression	

Sand	2001.17 g
Water	1003.00 g
Naphthol	0.2028 g

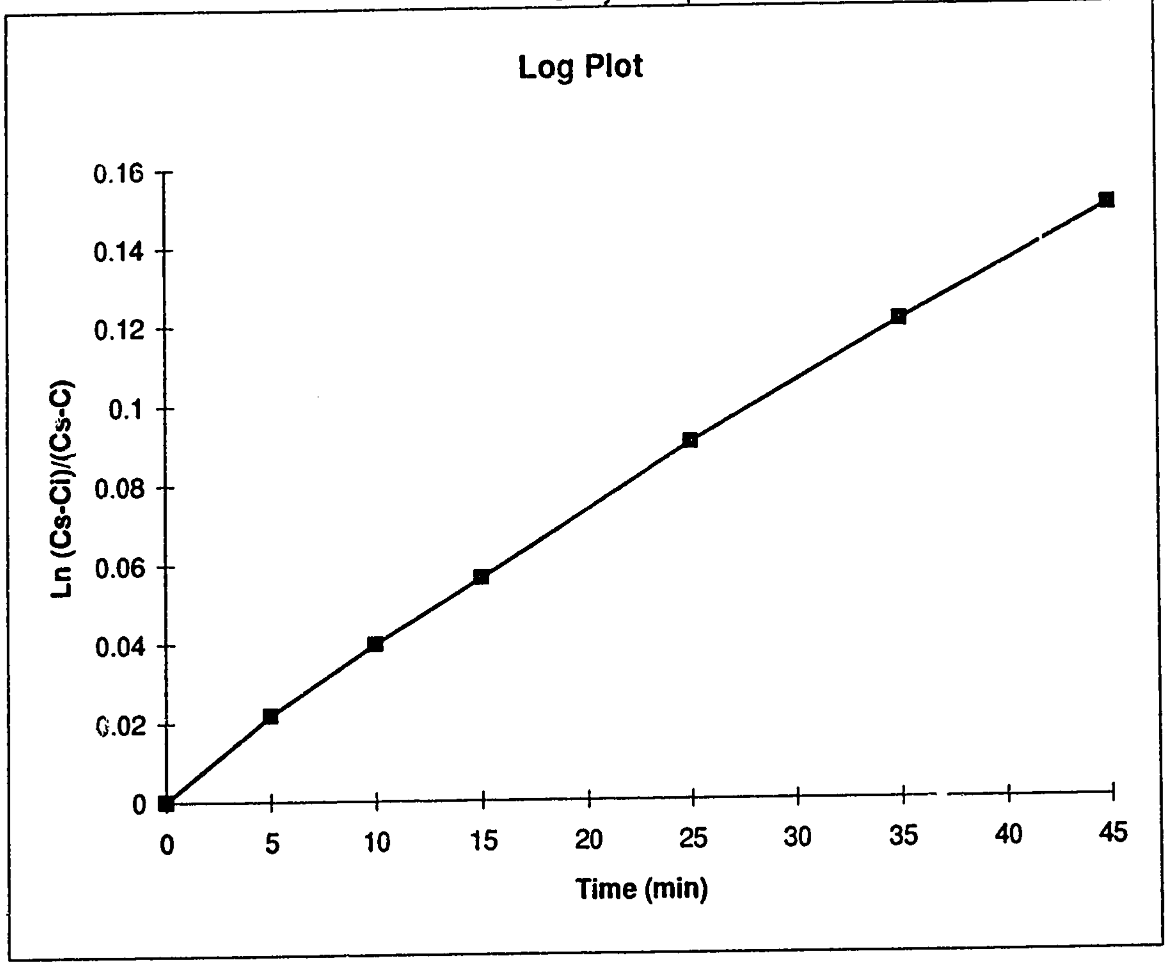
Sand and water pre-mixed for 10 minutes

Surface Area	2.16E-03 m2
Liquid Volume	1.00E-03 m3
Solid Volume	7.55E-04 m3
Total Volume	1.76E-03 m3

Ks = 2.86E-05 m/s

svf = 0.43

slurry holdup % = 8.6



Drum Rotational Speed Varying Set of Data

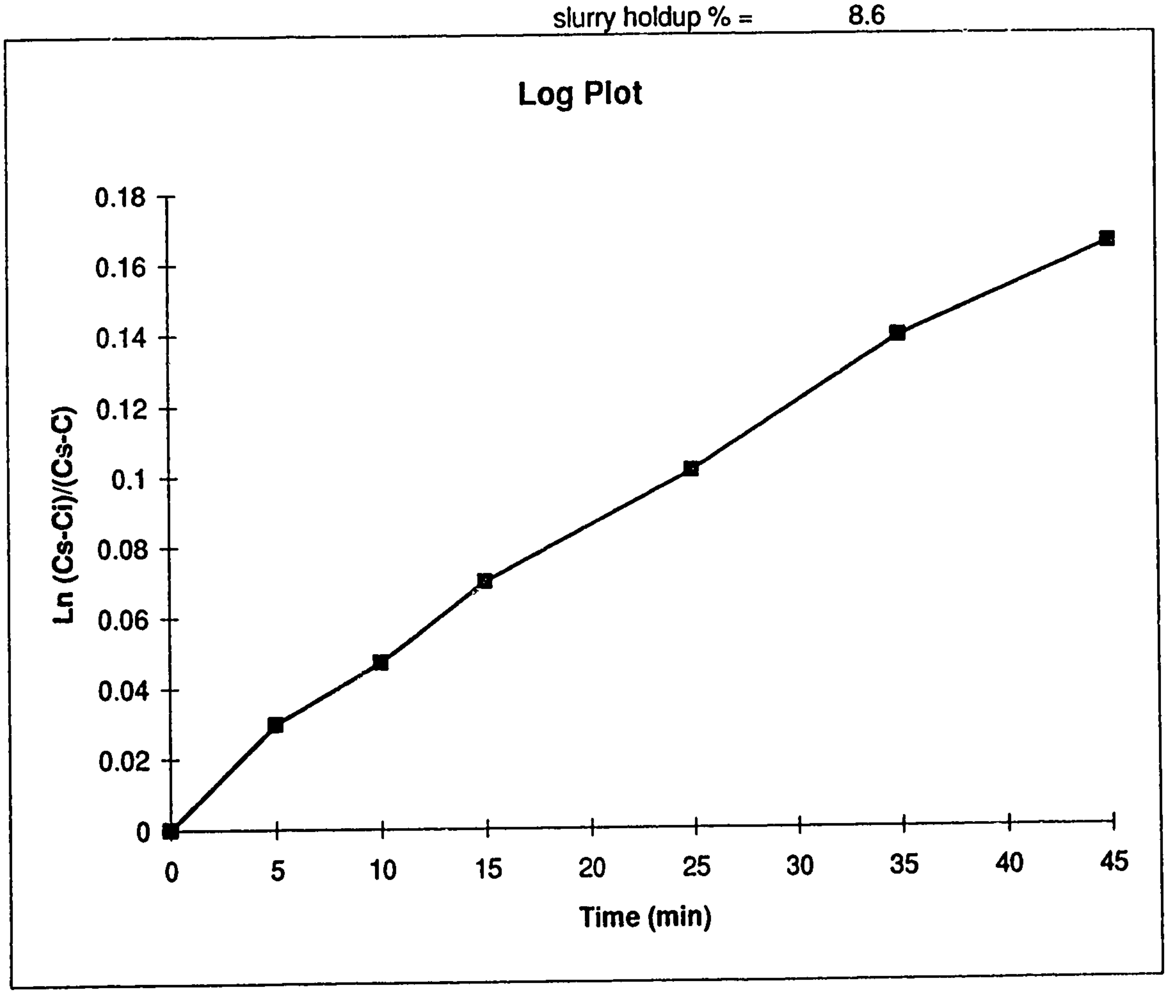
RUN 6	Sept 23/93	Sand and	Naphthol			
R.P.M.	11.01	Size	425-500 microns			
Cs (g/l)	0.74	4 Baffles				
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)	Regression	
1	0	0.075	0.0080	0	0.004303	0
2	5	0.286	0.0294	0.0297	0.000198	#N/A
3	10	0.407	0.0417	0.0471	0.974127	0.006192
4	15	0.562	0.0574	0.0699	150.6039	4
5	25	0.768	0.0784	0.1011	0.005775	0.000153
6	35	1.010	0.1030	0.1390		
7	45	1.173	0.1195	0.1653	Only the first 25 minutes of exp., is analyzed in regression	

Sand	2000.14 g		Surface Area	2.17E-03 m2
Water	1000.00 g		Liquid Volume	1.00E-03 m3
Naphthol	0.2040 g		Solid Volume	7.55E-04 m3
Sand and water pre-mixed for 10 minutes			Total Volume	1.76E-03 m3

Ks = 3.30E-05 m/s

svf = 0.43

slurry holdup % = 8.6



Drum Rotational Speed Varying Set of Data

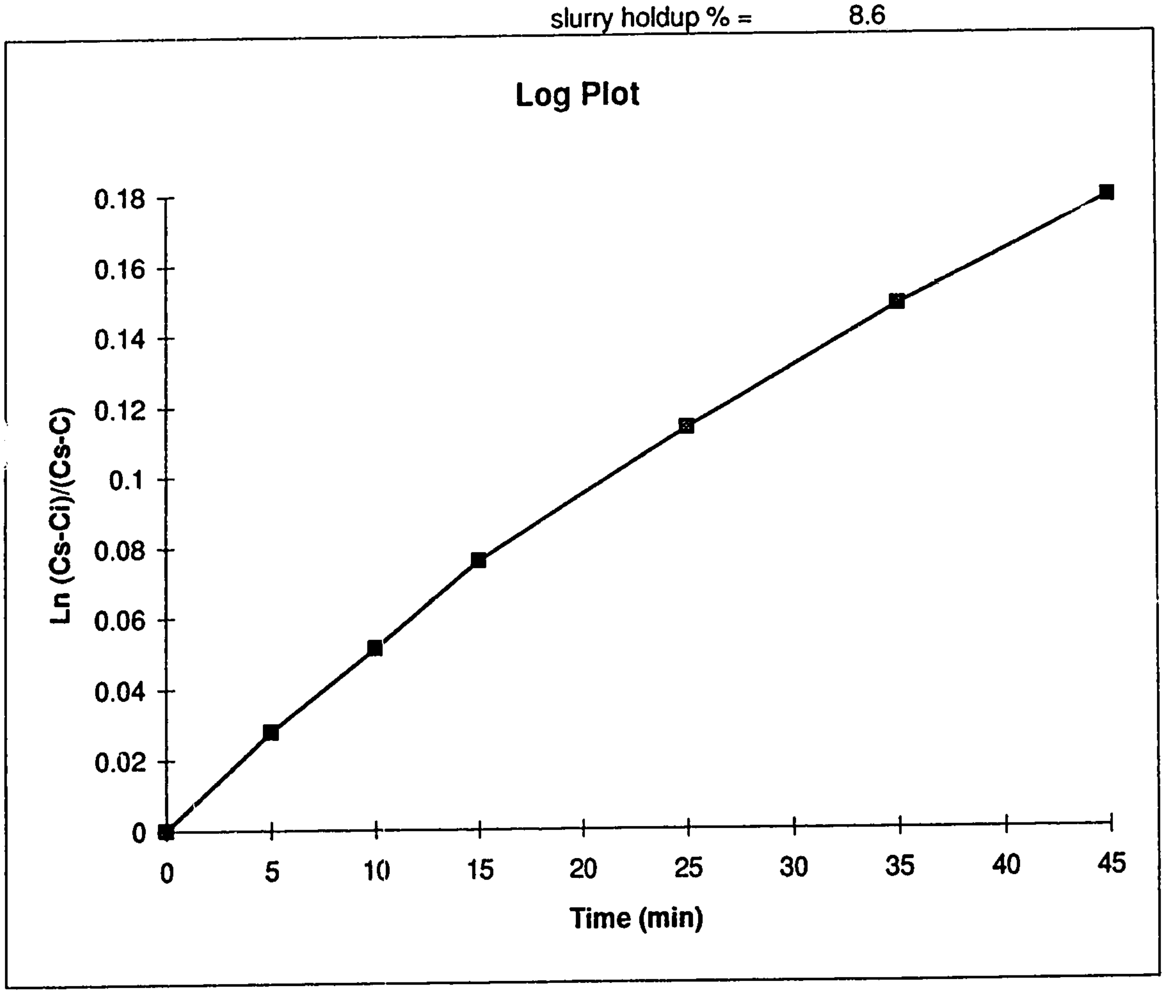
RUN 7	Sept 27/93	Sand and	Naphthol			
R.P.M.	12.90	Size	425-500	microns		
Cs (g/l)	0.74	4 Baffles				
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)	Regression	
1	0	0.102	0.0107	0	0.004744	0
2	5	0.299	0.0307	0.0278	0.000143	#N/A
3	10	0.460	0.0471	0.0512	0.989496	0.004473
4	15	0.627	0.0640	0.0759	376.7948	4
5	25	0.872	0.0889	0.1134	0.00754	8E-05
6	35	1.091	0.1111	0.1481		
7	45	1.275	0.1299	0.1785	Only the first 25 minutes of exp., is analyzed in regression	

Sand	2002.59	g	Surface Area	2.18E-03	m2
Water	1001.03	g	Liquid Volume	1.00E-03	m3
Naphthol	0.2049	g	Solid Volume	7.56E-04	m3
Sand and water pre-mixed for 10 minutes			Total Volume	1.76E-03	m3

Ks = 3.63E-05 m/s

svf = 0.43

slurry holdup % = 8.6



Drum Rotational Speed Varying Set of Data

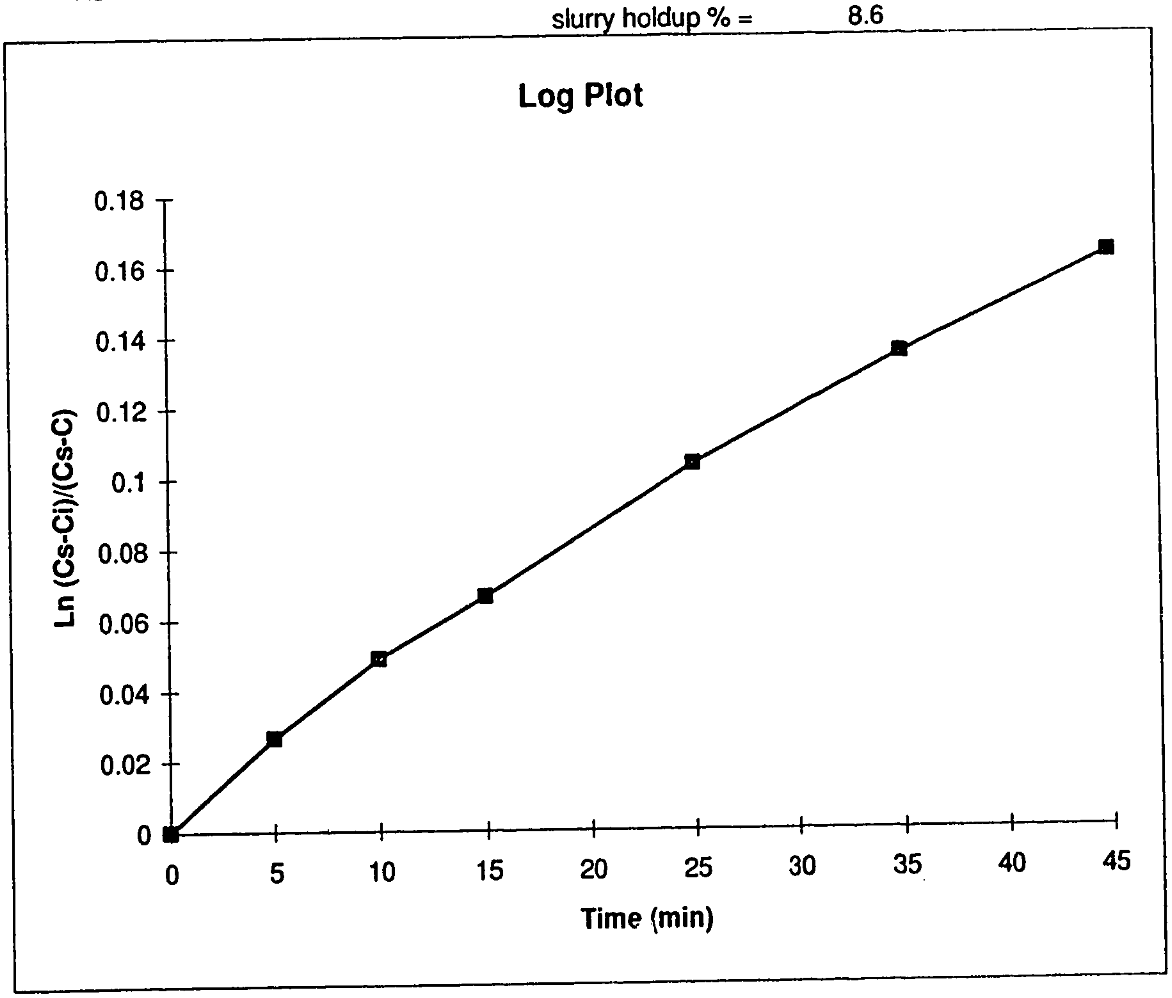
RUN 8	Sept 28/93	Sand and	Naphthol			
R.P.M.	14.93	Size	425-500 microns			
Cs (g/l)	0.74	4 Baffles				
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)	Regression	
1	0	0.114	0.0119	0	0.004311	0
2	5	0.301	0.0309	0.0264	0.000141	#N/A
3	10	0.455	0.0466	0.0488	0.987478	0.004399
4	15	0.574	0.0586	0.0663	315.4457	4
5	25	0.819	0.0835	0.1035	0.006103	7.74E-05
6	35	1.019	0.1038	0.1349		
7	45	1.191	0.1213	0.1628	Only the first 25 minutes of exp., is analyzed in regression	

Sand	2000.33 g	Surface Area	1.85E-03 m2
Water	1000.53 g	Liquid Volume	1.00E-03 m3
Naphthol	0.1736 g	Solid Volume	7.55E-04 m3
Sand and water pre-mixed for 10 minutes		Total Volume	1.76E-03 m3

Ks = 3.89E-05 m/s

svf = 0.43

slurry holdup % = 8.6



Drum Rotational Speed Varying Set of Data

RUN 9	Oct 5/93	Sand and	Naphthol				
R.P.M.	14.89	Size	425-500 microns				
Cs (g/l)	0.74	4 Baffles					
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)		Regression	
1	0	0.073	0.0077	0		0.005409	0
2	5	0.320	0.0329	0.0350		0.00022	#N/A
3	10	0.505	0.0516	0.0618		0.980155	0.006859
4	15	0.661	0.0674	0.0850		197.5583	4
5	25	0.939	0.0958	0.1282		0.009295	0.000188
6	35	1.169	0.1191	0.1650			
7	45	1.354	0.1379	0.1958	Only the first 25 minutes of exp., is analyzed in regression		

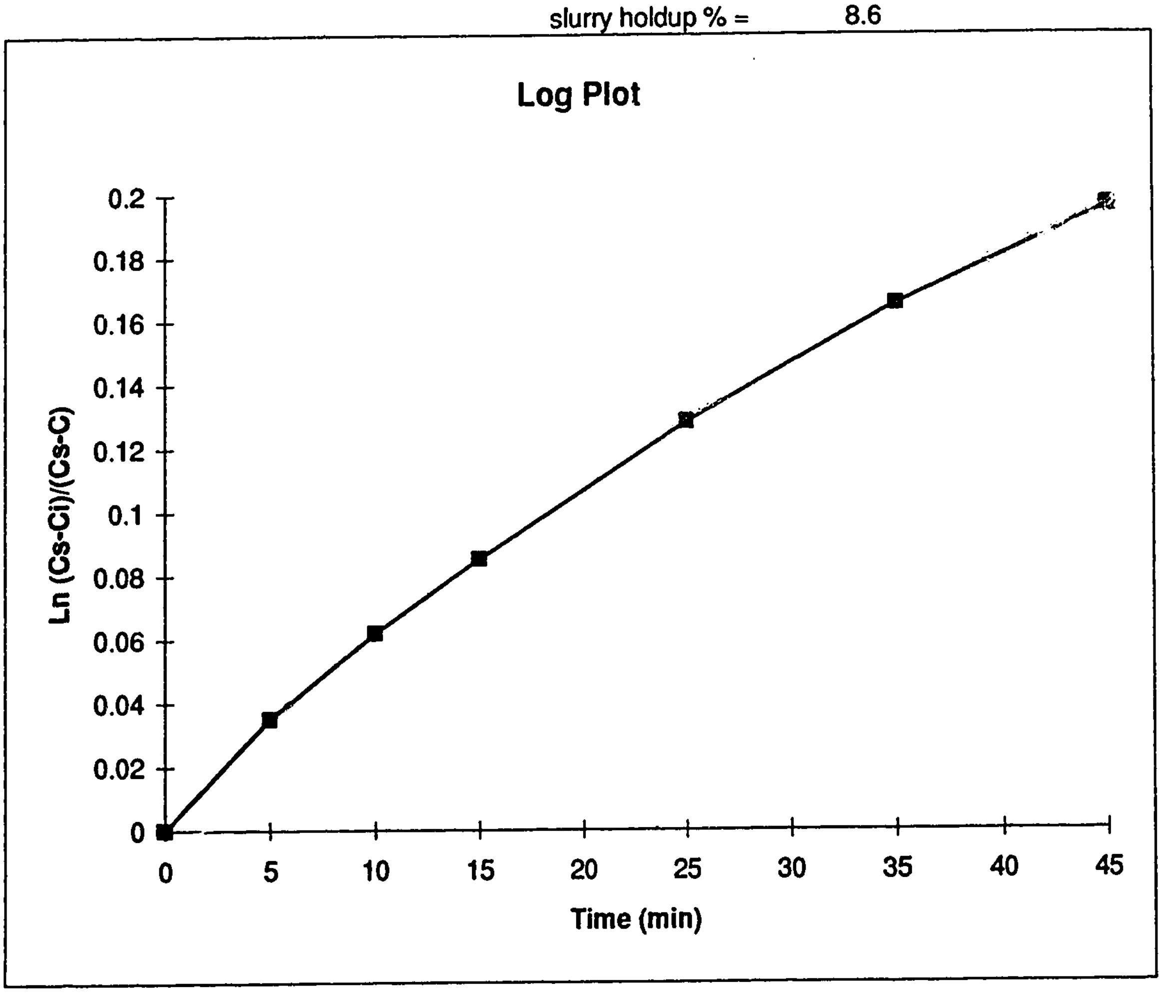
This run is a check on the ks from run 8 above

Sand	2002.90	g	Surface Area	2.18E-03	m2
Water	1003.41	g	Liquid Volume	1.01E-03	m3
Naphthol	0.2048	g	Solid Volume	7.56E-04	m3
Sand and water pre-mixed for 10 minutes			Total Volume	1.76E-03	m3

Ks = 4.15E-05 m/s

svf = 0.43

slurry holdup % = 8.6



Drum Rotational Speed Varying Set of Data

RUN 10	Oct 6/93	Sand and	Naphthol			
R.P.M.	1.15	Size	425-500 microns			
Cs (g/l)	0.74	4 Baffles				
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)	Regression	
1	0	0.059	0.0063	0	0.001537	0
2	5	0.153	0.0159	0.0132	0.000127	#N/A
3	10	0.194	0.0200	0.0188	0.906862	0.003965
4	15	0.240	0.0247	0.0254	38.9468	4
5	25	0.304	0.0312	0.0345	0.000612	6.29E-05
6	45	0.448	0.0458	0.0553		

Only the first 25 minutes of exp., is analyzed in regression

Sand	1999.74 g
Water	1002.93 g
Naphthol	0.2103 g

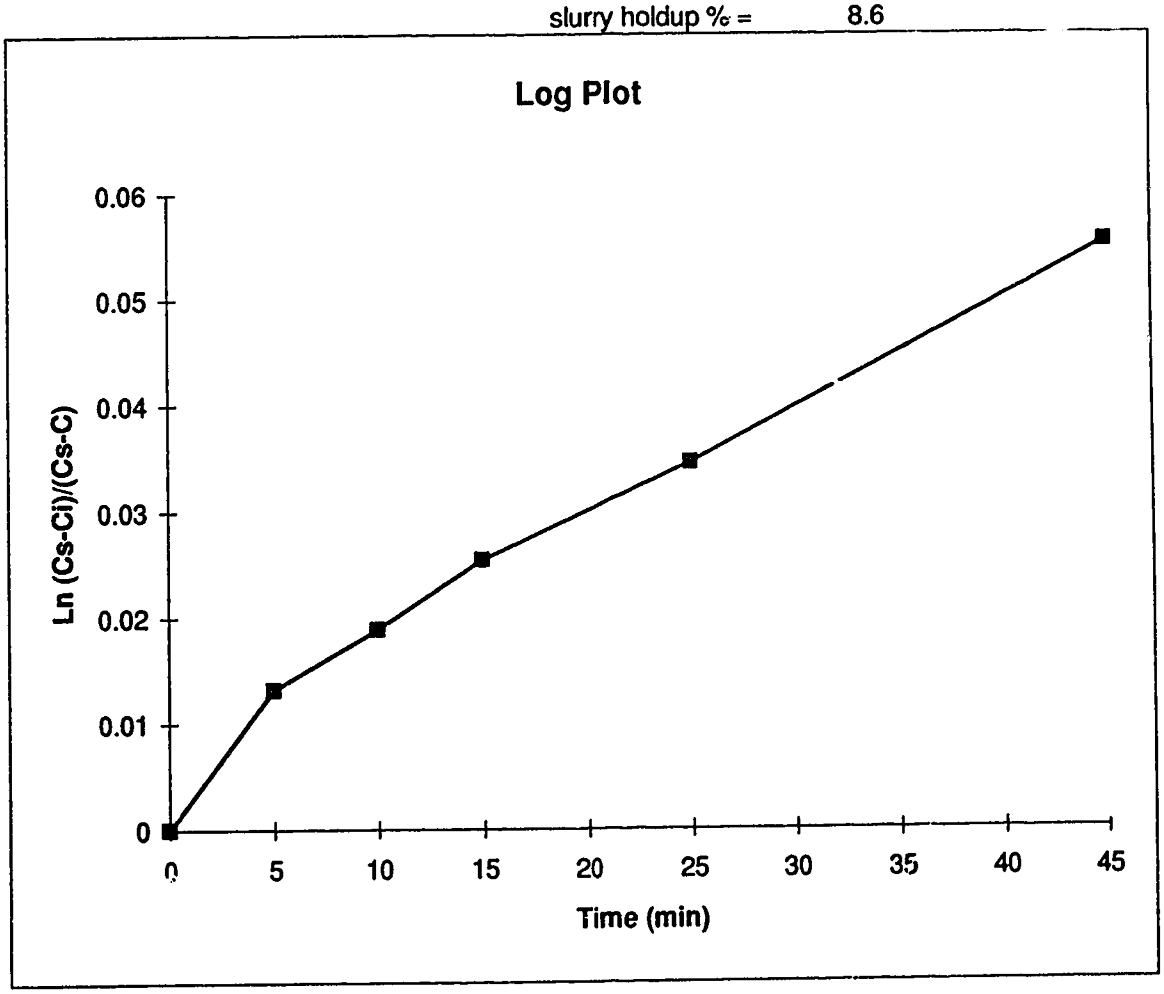
Sand and water pre-mixed for 10 minutes

Surface Area	2.24E-03 m2
Liquid Volume	1.00E-03 m3
Solid Volume	7.55E-04 m3
Total Volume	1.76E-03 m3

Ks = 1.15E-05 m/s

svf = 0.43

slurry holdup % = 8.6



Drum Rotational Speed Varying Set of Data

RUN 11	Oct12/93	Sand and	Naphthol			
R.P.M.	0.38	Size	425-500	microns		
Cs (g/l)	0.74	4 Baffles				
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)	Regression	
1	0	0.041	0.0045	0	0.001412	0
2	5	0.112	0.0117	0.0098	0.00013	#N/A
3	10	0.181	0.0187	0.0195	0.887541	0.004068
4	15	0.214	0.0221	0.0242	31.56861	4
5	25	0.260	0.0268	0.0308	0.000522	6.62E-05
6	35	0.305	0.0313	0.0371		
7	45	0.354	0.0362	0.0441	Only the first 25 minutes of exp., is analyzed in regression	

Sand	1999.67	g
Water	1006.72	g
Naphthol	0.2046	g

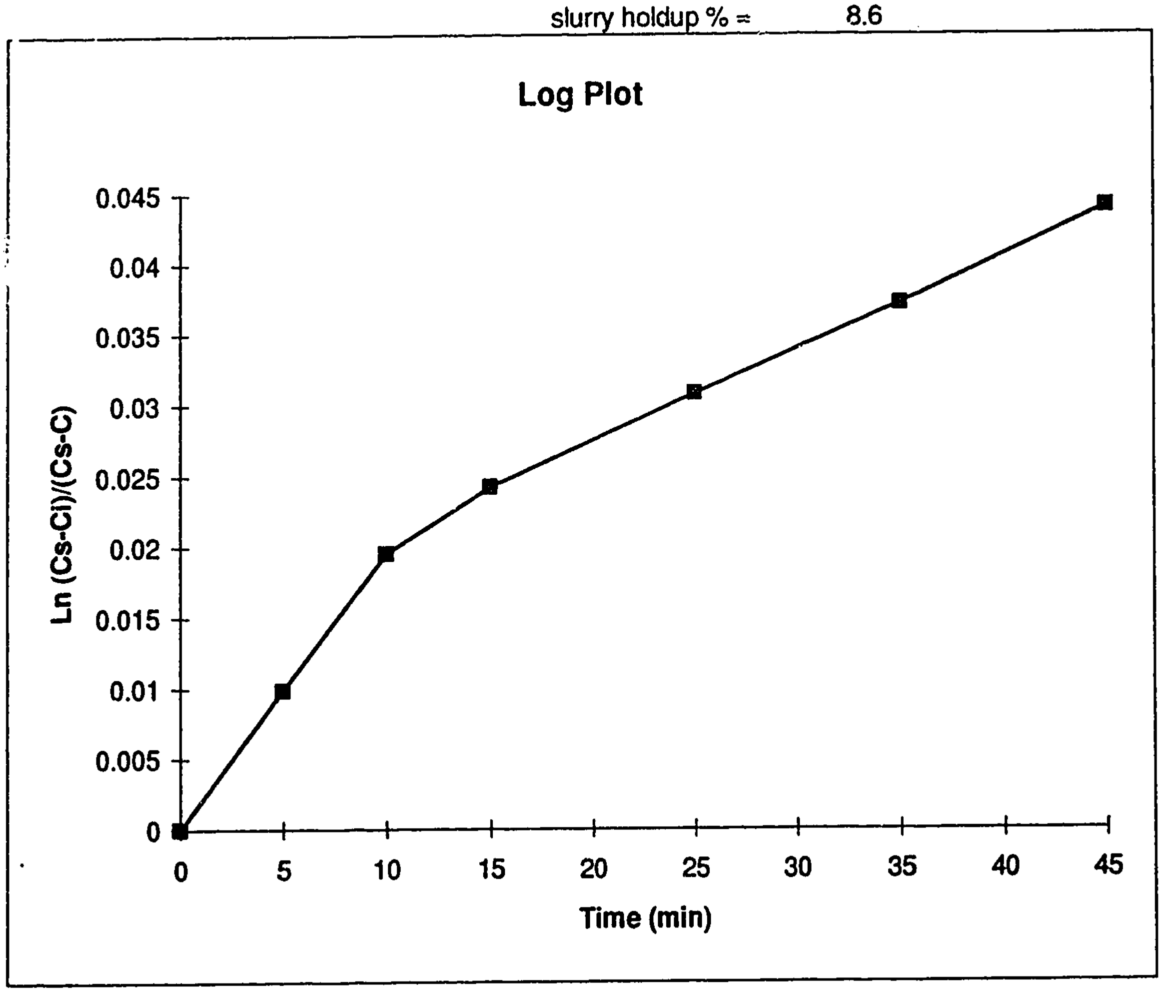
Sand and water pre-mixed for 10 minutes

Surface Area	2.18E-03	m2
Liquid Volume	1.01E-03	m3
Solid Volume	7.55E-04	m3
Total Volume	1.76E-03	m3

Ks = 1.09E-05 m/s

svf = 0.43

slurry holdup % = 8.6



Drum Rotational Speed Varying Set of Data

RUN 12	Oct 15/93	Sand and	Naphthol				
R.P.M.	0.50	Size	425-500	microns			
Cs (g/l)	0.74	4 Baffles					
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)		Regression	
1	0	0.044	0.0049	0		0.001298	0
2	5	0.108	0.0113	0.0087		4.87E-05	#N/A
3	10	0.130	0.0136	0.0119		0.985032	0.001519
4	15	0.174	0.0180	0.0180		263.2281	4
5	25	0.282	0.0290	0.0333		0.000608	9.23E-06
6	35	0.324	0.0332	0.0393			
7	45	0.375	0.0384	0.0466	Only the first 25 minutes of exp., is analyzed in regression		

Sand	2001.51	g
Water	1004.82	g
Naphthol	0.2099	g

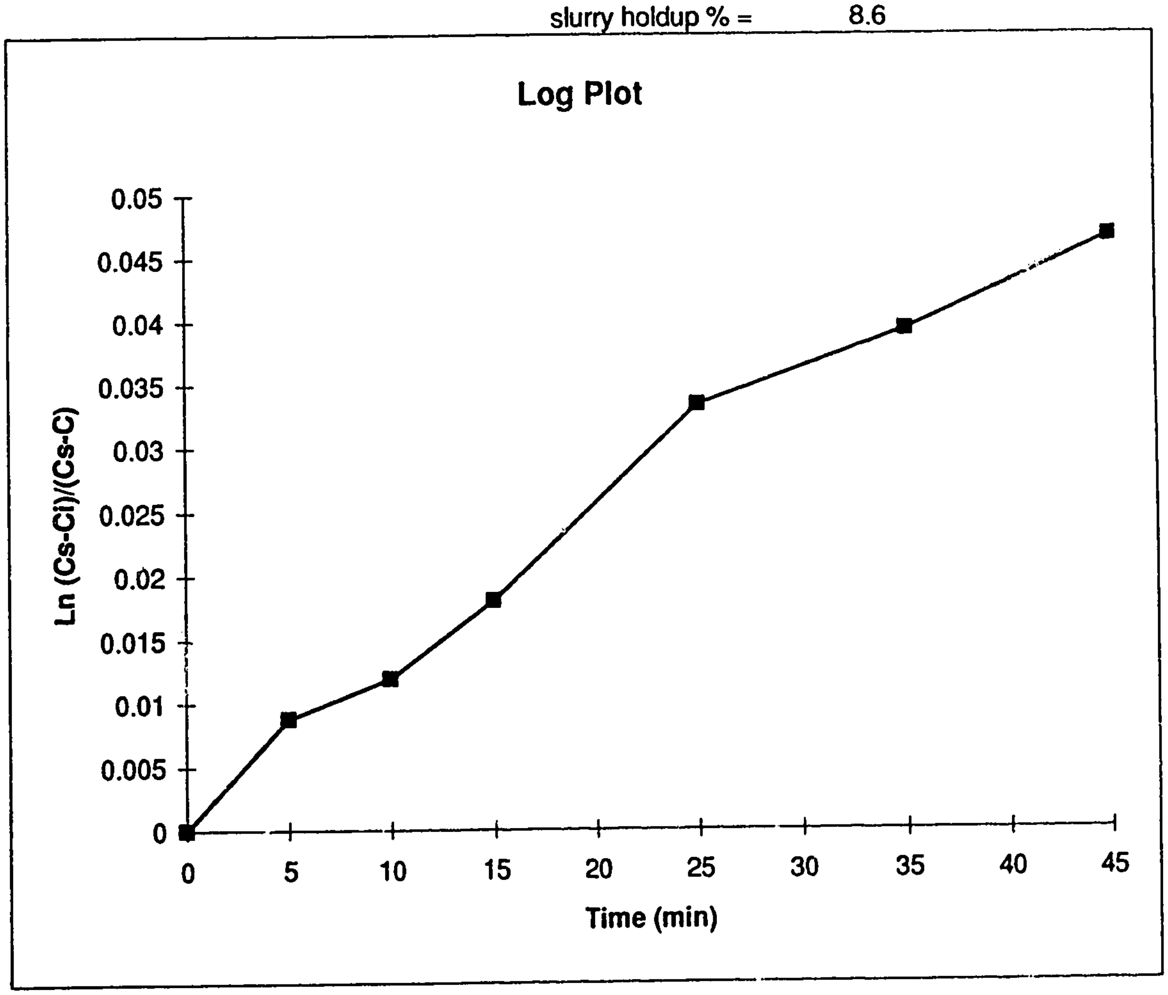
Sand and water pre-mixed for 10 minutes

Surface Area	2.24E-03	m2
Liquid Volume	1.01E-03	m3
Solid Volume	7.55E-04	m3
Total Volume	1.76E-03	m3

Ks = 9.74E-06 m/s

svf = 0.43

slurry holdup % = 8.6



Drum Rotational Speed Varying Set of Data

RUN 13	Oct 21/93	Sand and	Naphthol			
R.P.M.	2.11	Size	425-500	microns		
Cs (g/l)	0.74	4 Baffles				
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)	Regression	
1	0	0.050	0.0054	0	0.001827	0
2	5	0.158	0.0164	0.0151	0.000125	#N/A
3	10	0.208	0.0215	0.0222	0.938618	0.003896
4	15	0.250	0.0257	0.0280	61.16607	4
5	25	0.352	0.0360	0.0425	0.000929	6.07E-05
6	35	0.457	0.0467	0.0579		
7	45	0.544	0.0556	0.0708		

Only the first 25 minutes of exp., is analyzed in regression

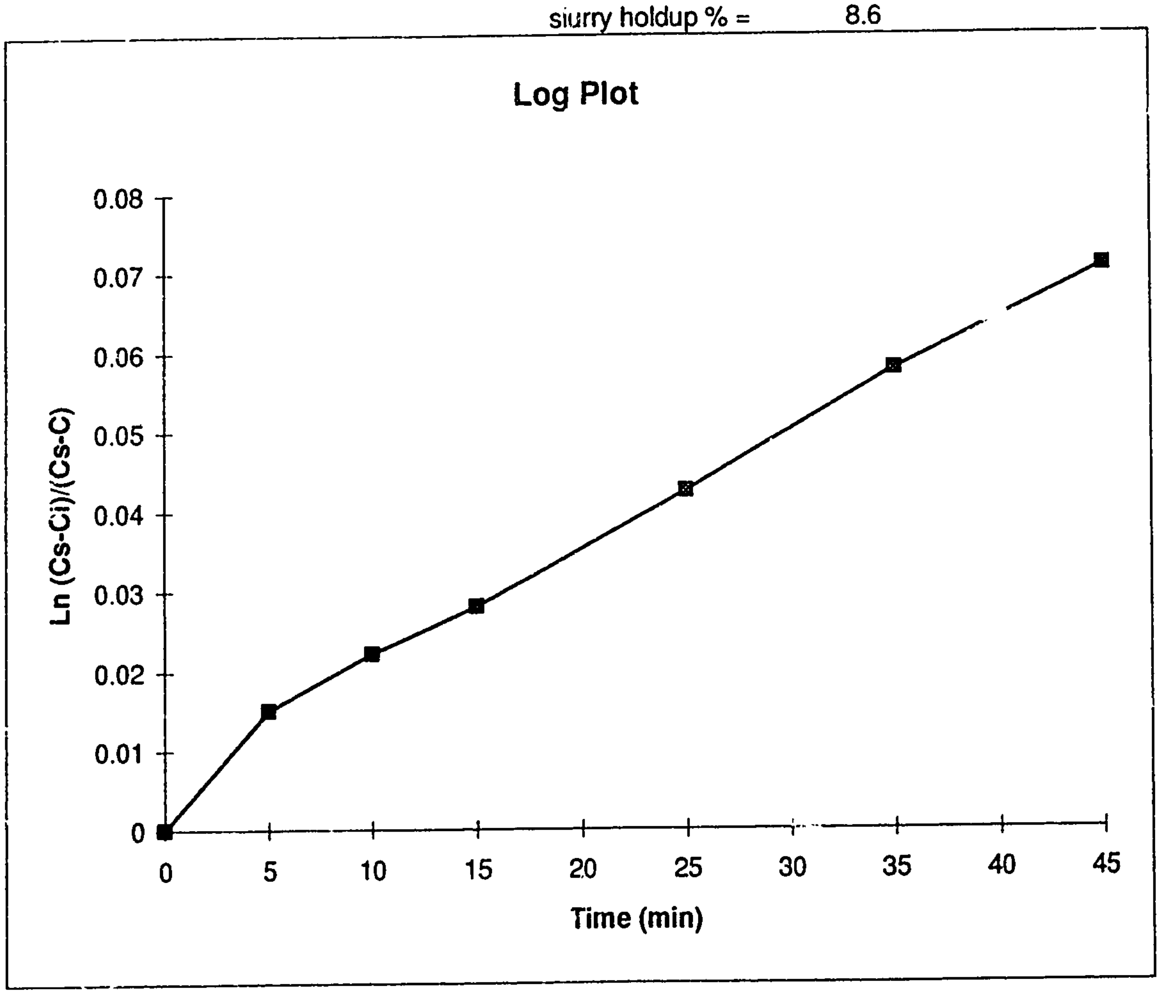
Sand	1998.25	g	Surface Area	2.39E-03	m2
Water	999.90	g	Liquid Volume	1.00E-03	m3
Naphthol	0.2243	g	Solid Volume	7.54E-04	m3
			Total Volume	1.76E-03	m3

Sand and water pre-mixed for 10 minutes

Ks = 1.28E-05 m/s

svf = 0.43

slurry holdup % = 8.6



Drum Rotational Speed Varying Set of Data

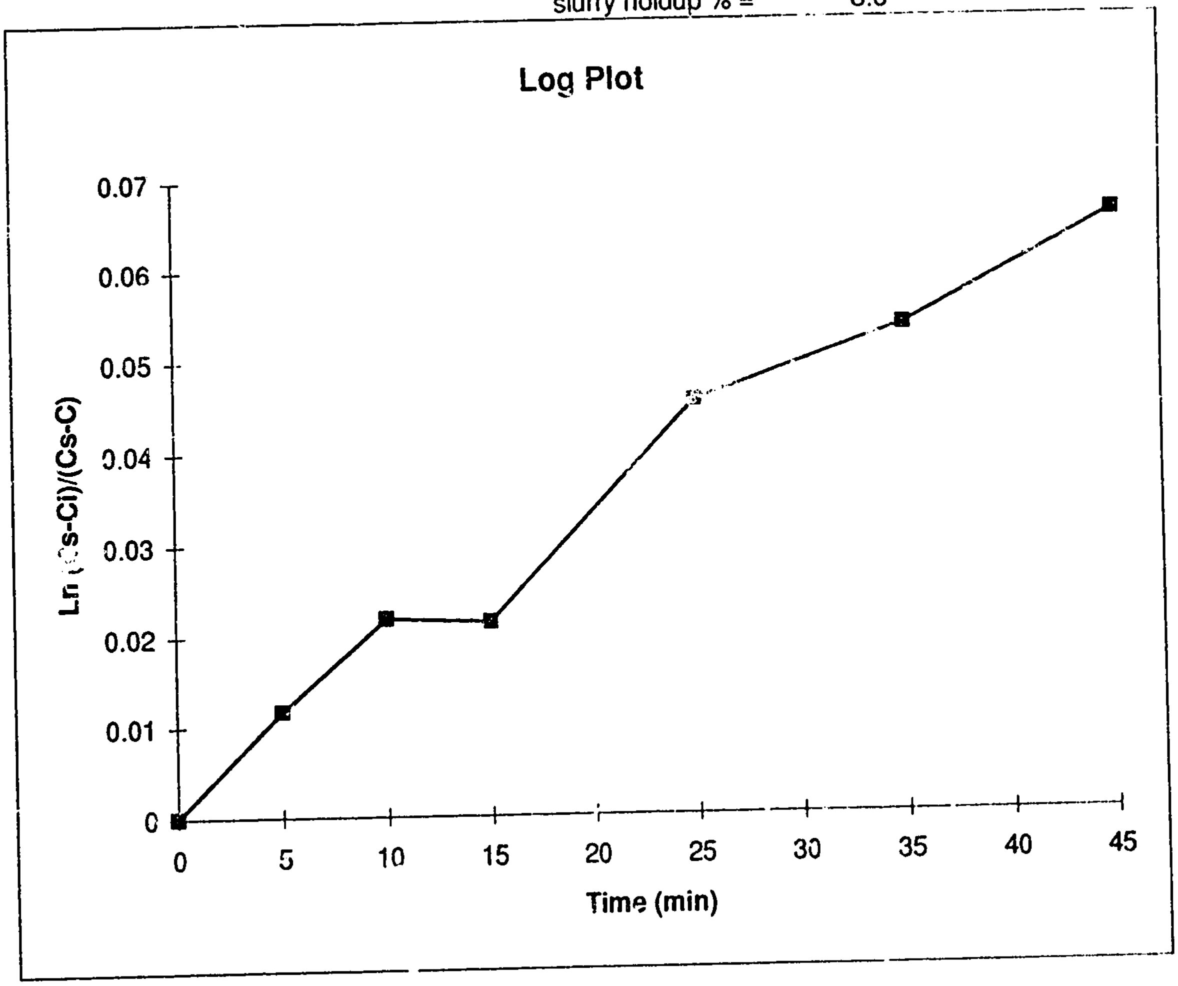
RUN 14	Nov 1/93	Sand and	Naphthol			
R.P.M.	0.33	Size	425-500 microns			
Cs (g/l)	0.74	4 Baffles				
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)	Regression	
1	0	0.082	0.0087	0	0.001779	0
2	5	0.166	0.0172	0.0117	0.000116	#N/A
3	10	0.238	0.0245	0.0218	0.95288	0.003636
4	15	0.235	0.0242	0.0214	80.88967	4
5	25	0.402	0.0412	0.0455	0.00107	5.29E-05
6	35	0.457	0.0468	0.0535		
7	45	0.541	0.0553	0.0658	Only the first 25 minutes of exp., is analyzed in regression	

Sand	2000.12 g		Surface Area	2.21E-03 m2
Water	100[illegible] g		Liquid Volume	1.01E-03 m3
Naphthol	0.20[illegible] g		Solid Volume	7.55E-04 m3
Sand and water pre-mixed for 20 minutes			Total Volume	1.76E-03 m3

Ks = 1.35E-05 m/s

svt = 0.43

slurry holdup % = 8.6



Slurry Holdup Varying Set of Data

RUN 1 Nov 3/93 Sand and Naphthol

R.P.M.	3.22	Size	425-500 micron	
Cs (g/l)	0.74	4 Baffles		

Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)
1	0	0.077	0.0081	0.0000
2	5	0.543	0.0555	0.0670
3	10	0.429	0.0439	0.0502
4	15	0.535	0.0547	0.0658
5	25	0.677	0.0691	0.0870
6	35	0.802	0.0818	0.1061
7	45	0.942	0.0960	0.1279

Regression

0.003188	0
0.000376	#N/A
0.650292	0.024438
11.15718	6
0.006663	0.003583

Sand	998.94 g
Water	508.14 g
Naphthol	0.2046 g

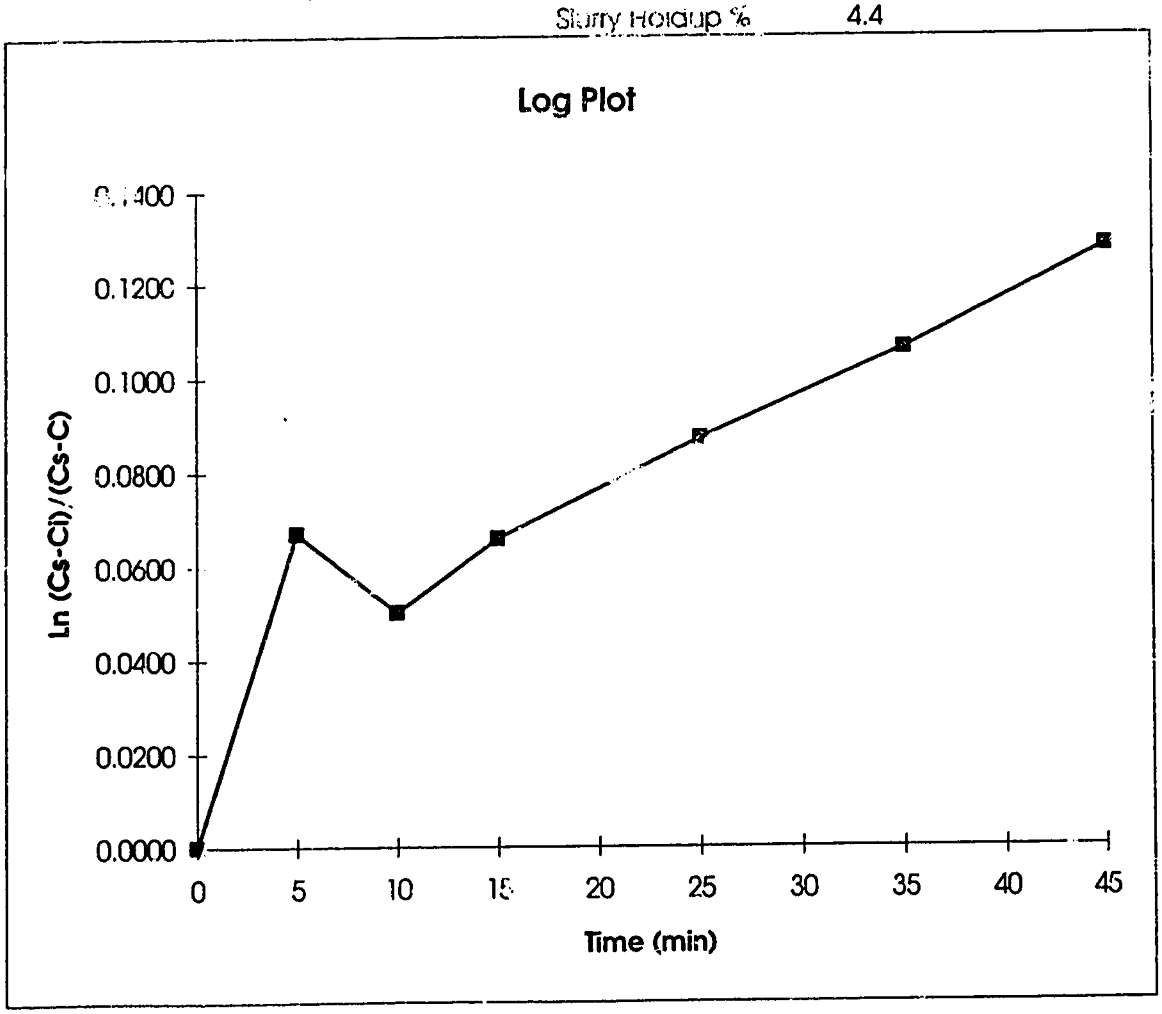
Sand and water pre-mixed for 10 minutes

Surface Area	2.18E-03 m2
Liquid Volume	5.09E-04 m3
Solid Volume	3.77E-04 m3
Total Volume	8.86E-04 m3

Ks = 1.24E-05 m/s

[illegible] f = 0.43

Slurry Holdup % 4.4



Slurry Holdup Varying Set of Data

RUN 2 Nov 4/'93 Sand and Naphthol

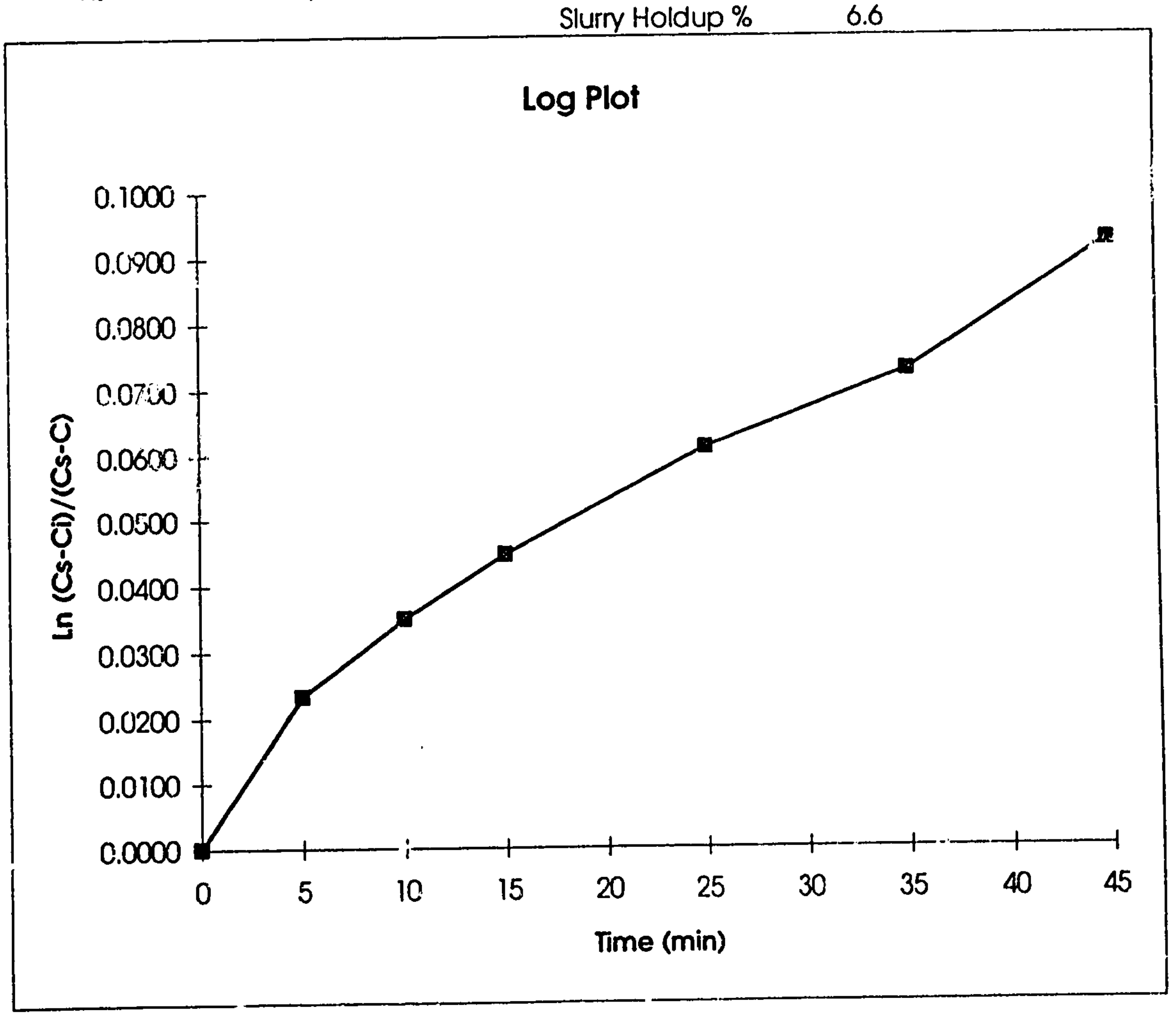
R.P.M.	3.10	Size	425-500 micron			
Cs (g/l)	0.74	4 Baffles				
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)	Regression	
1	0	0.115	0.0120	0.0000	0.002216	0
2	5	0.279	0.0287	0.0232	0.000147	#N/A
3	10	0.361	0.0370	0.0349	0.905787	0.009577
4	15	0.428	0.0438	0.0447	57.6853	6
5	25	0.539	0.0551	0.0610	0.005291	0.00055
6	35	0.618	0.0631	0.0728		
7	45	0.747	0.0762	0.09[illegible]3		

Sand	1501.60 g	Surface Area	2.22E-03 m2
Water	751.42 g	Liquid Volume	7.53E-04 m3
Naphthol	0.2079 g	Solid Volume	5.67E-04 m3
Sand and water pre-mixed for 10 minutes		Total Volume	1.32E-03 m3

Ks = 1.25E-05 m/s

svf = 0.43

Slurry Holdup % 6.6



Slurry Holdup Varying Set of Data

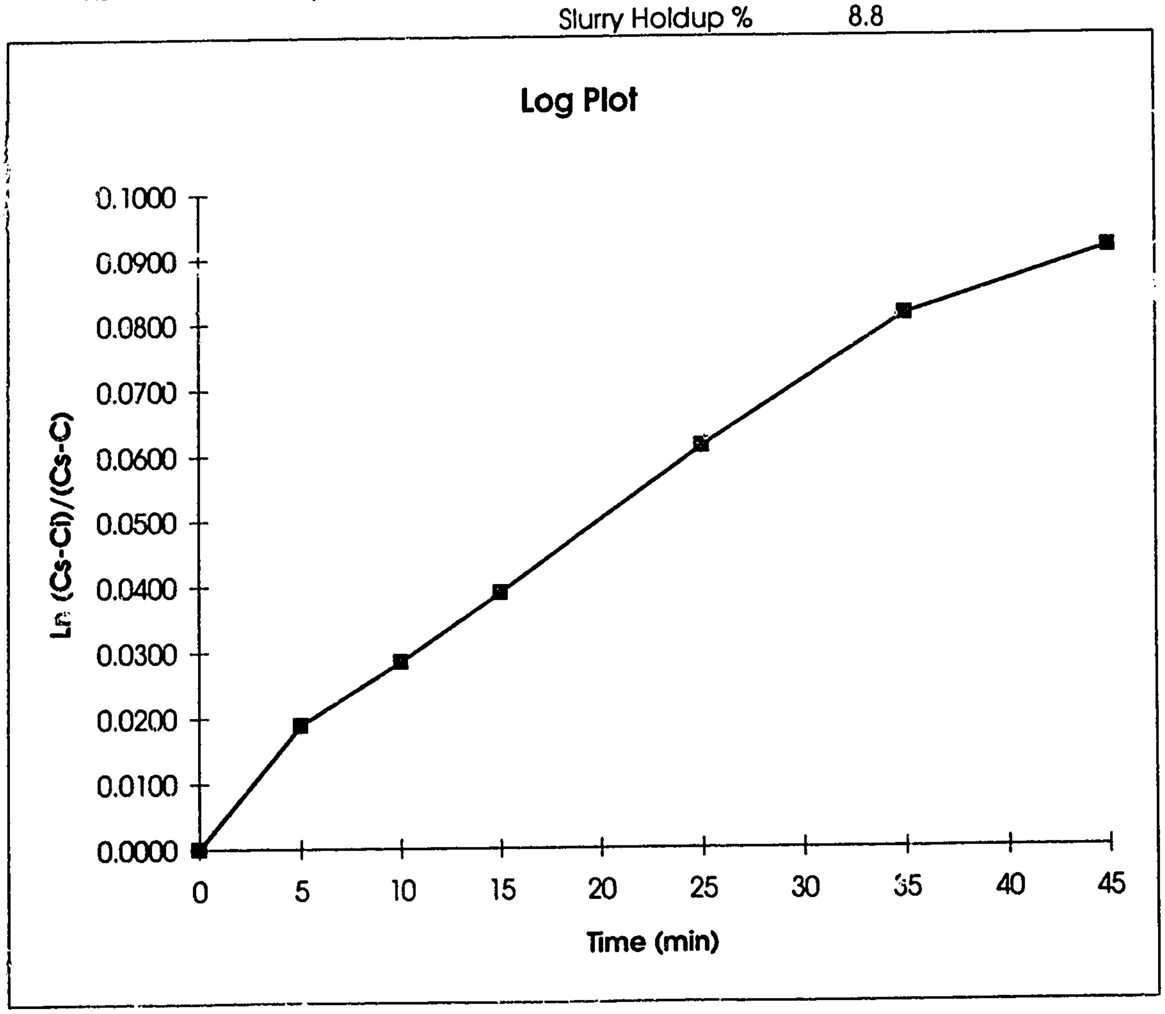
RUN 3	Nov 9/93	Sand and Naphthol					
R.P.M.	3.19	Size	425-500 micron				
Cs (g/l)	0.74	4 Baffles					
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)		Regression	
1	0	0.064	0.0068	0.0000		0.002236	0
2	5	0.197	0.0204	0.0187		9.86E-05	#N/A
3	10	0.265	0.0273	0.0284		0.963527	0.006406
4	15	0.339	0.0348	0.0389		158.5045	6
5	25	0.493	0.0504	0.0613		0.006505	0.000246
6	35	0.626	0.0640	0.0812			
7	45	0.693	0.0708	0.0913			

Sand	2001.52 g	Surface Area	2.19E-03 m2
Water	1005.87 g	Liquid Volume	1.01E-03 m3
Naphthol	0.2053 g	Solid Volume	7.55E-04 m3
Sand and water pre-mixed for 10 minutes		Total Volume	1.76E-03 m3

Ks = 1.72E-05 m/s

svf = 0.43

Slurry Holdup % 8.8



Slurry Holdup Varying Set of Data

RUN 4 Nov 10/93 Sand and Naphthol

R.P.M. 3.17 Size 425-500 micron

Cs (g/l) 0.74 4 Baffles

Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)
1	0	0.078	0.0082	0.0000
2	5	0.170	0.0176	0.0129
3	10	0.243	0.0250	0.0232
4	15	0.318	0.0326	0.0339
5	25	0.445	0.0456	0.0525
6	35	0.550	0.0562	0.0678
7	45	0.686	0.0700	0.0882

Regression	
0.002003	0
4.35E-05	#N/A
0.991862	0.002831
731.2839	6
0.005859	4.81E-05

Sand	2500.56 g
Water	1251.34 g
Naphthol	0.2038 g

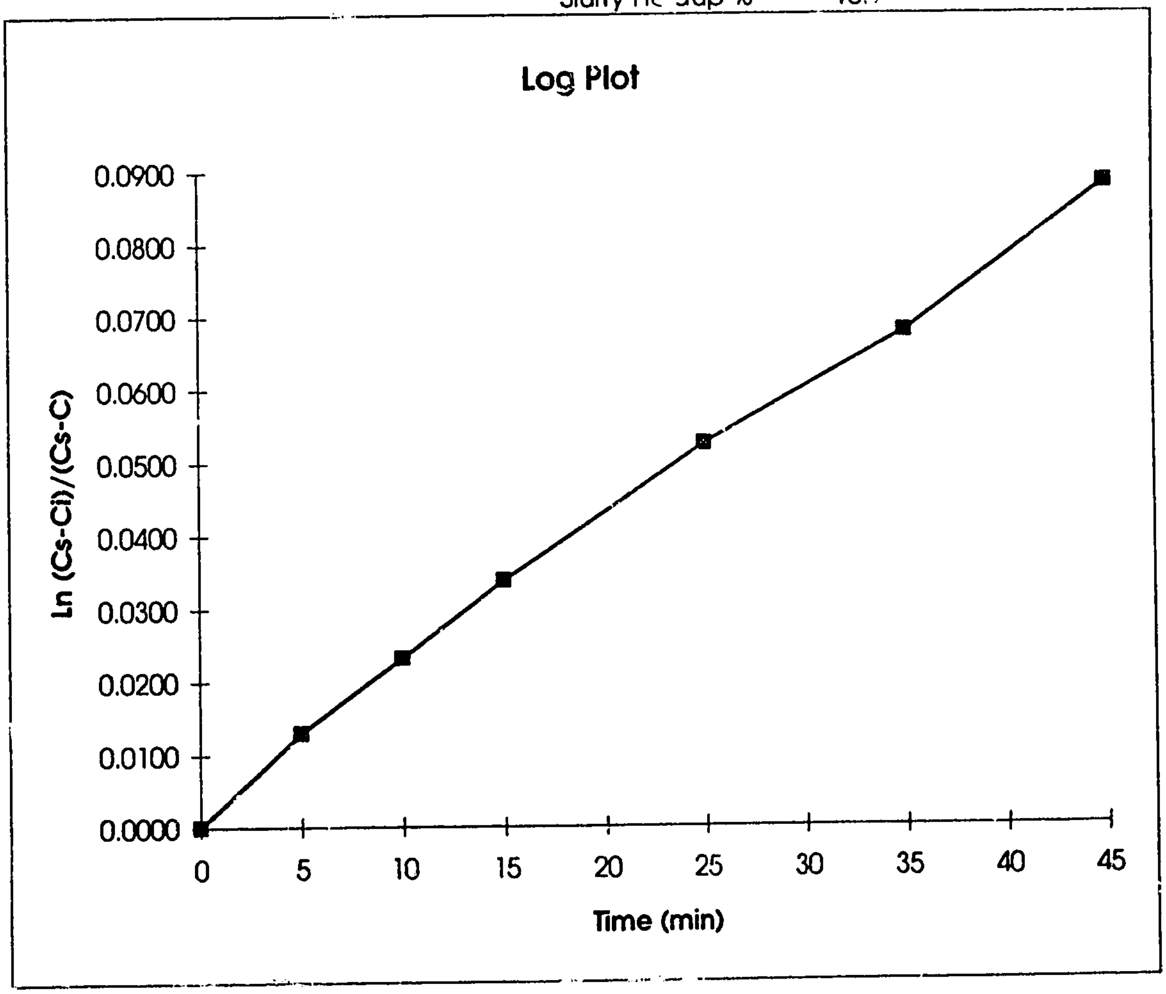
Sand and water pre-mixed for 10 minutes

Surface Area	2.17E-03 m2
Liquid Volume	1.25E-03 m3
Solid Volume	9.44E-04 m3
Total Volume	2.20E-03 m3

Ks = 1.93E-05 m/s

svf = 0.43

Slurry Holdup % 10.9



Slurry Holdup Varying Set of Data

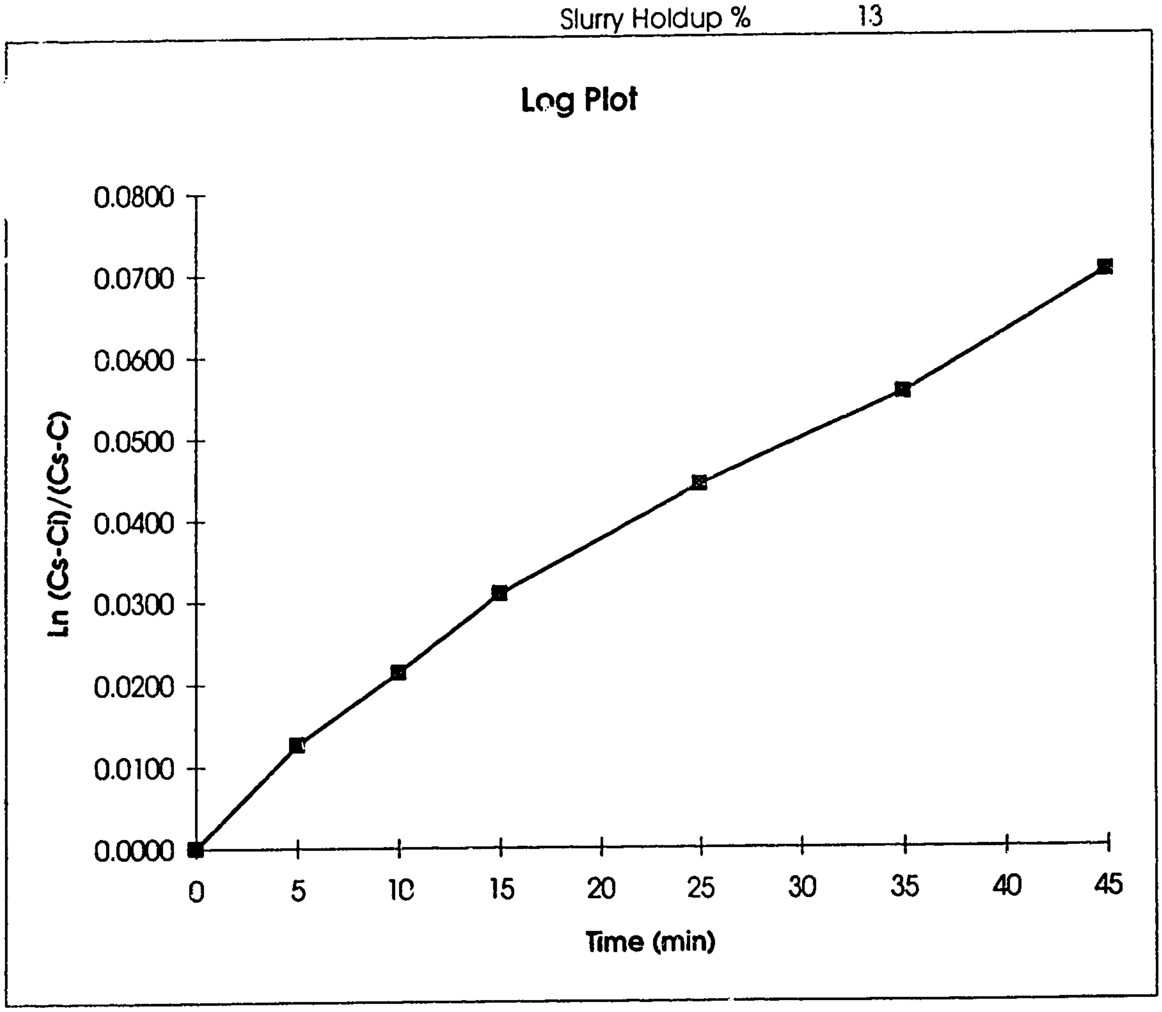
RUN 5	Nov 12/93	Sand and Naphthol					
R.P.M.	2.95	Size	425-500 micron				
Cs (g/l)	0.74	4 Baffles					
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)		Regression	
1	0	0.070	0.0074	0.0000		0.001644	0
2	5	0.160	0.0166	0.0126		6.62E-05	#N/A
3	10	0.223	0.0229	0.0214		0.969583	0.004306
4	15	0.289	0.0297	0.0309		191.2553	6
5	25	0.382	0.0391	0.0442		0.003546	0.000111
6	35	0.458	0.0469	0.0554			
7	45	0.559	0.0571	0.0703			

Sand	3002.16 g	Surface Area	2.23E-03 m2
Water	1501.64 g	Liquid Volume	1.50E-03 m3
Naphthol	0.2092 g	Solid Volume	1.13E-03 m3
Sand and water pre-mixed for 10 minutes		Total Volume	2.64E-03 m3

Ks = 1.85E-05 m/s

svf = 0.43

Slurry Holdup % 13



Slurry Holdup Varying Set of Data

RUN 6 Nov 16/93 Sand and Naphthol

R.P.M. 3.05 Size 425-500 micron

Cs (g/l) 0.74 4 Baffles

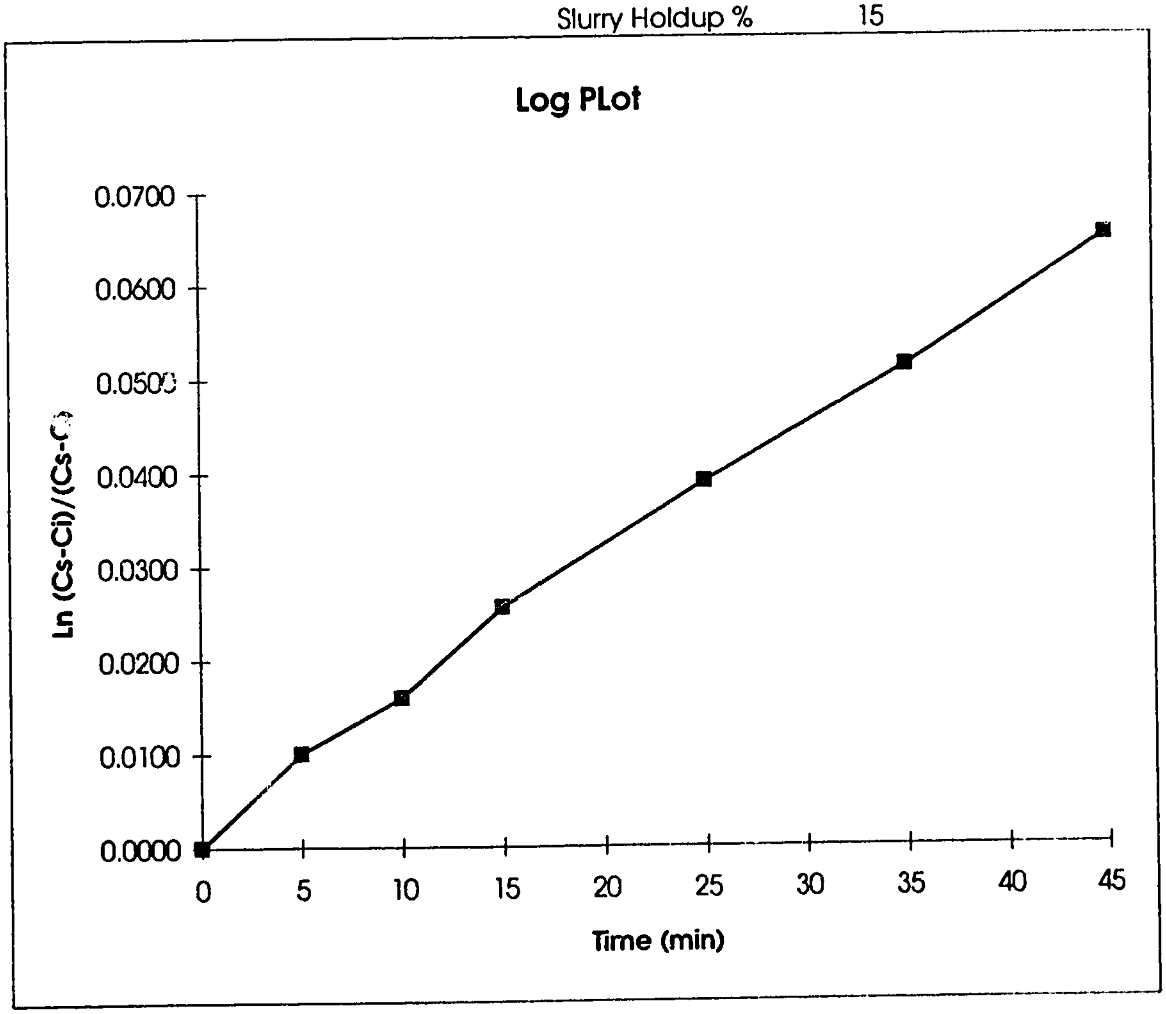
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)		Regression	
1	0	0.064	0.0068	0.0000		0.001488	0
2	5	0.135	0.0141	0.0100		3.17E-05	#N/A
3	10	0.178	0.0184	0.0159		0.992218	0.002061
4	15	0.246	0.0253	0.0256		765.0463	6
5	25	0.339	0.0348	0.0389		0.00325	2.55E-05
6	35	0.424	0.0434	0.0512			
7	45	0.518	0.0530	0.0651			

Sand	3501.12 g		Surface Area	2.54E-03 m2
Water	1750.44 g		Liquid Volume	1.75E-03 m3
Naphthol	0.2381 g		Solid Volume	1.32E-03 m3
Sand and water pre-mixed for 10 minutes			Total Volume	3.07E-03 m3

Ks = 1.71E-05 m/s

svf = 0.43

Slurry Holdup % 15



Slurry Holdup Varying Set of Data

RUN 7 Nov 29/93 Sand and Naphthol

R.P.M. 3.18 Size 425-500 micron

Cs (g/l) 0.74 4 Baffles

Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)
1	0	0.052	0.0056	0.0000
2	5	0.173	0.0179	0.0169
3	10	0.257	0.0264	0.0287
4	15	0.333	0.0342	0.0397
5	25	0.480	0.0491	0.0611
6	35	0.602	0.0614	0.0790
7	45	0.732	0.0747	0.0988

Regression

0.002297	0
7.05E-05	#N/A
0.982998	0.004581
346.9027	6
0.007281	0.000126

Sand	2001.88 g
Water	1002.33 g
Naphthol	0.2058 g

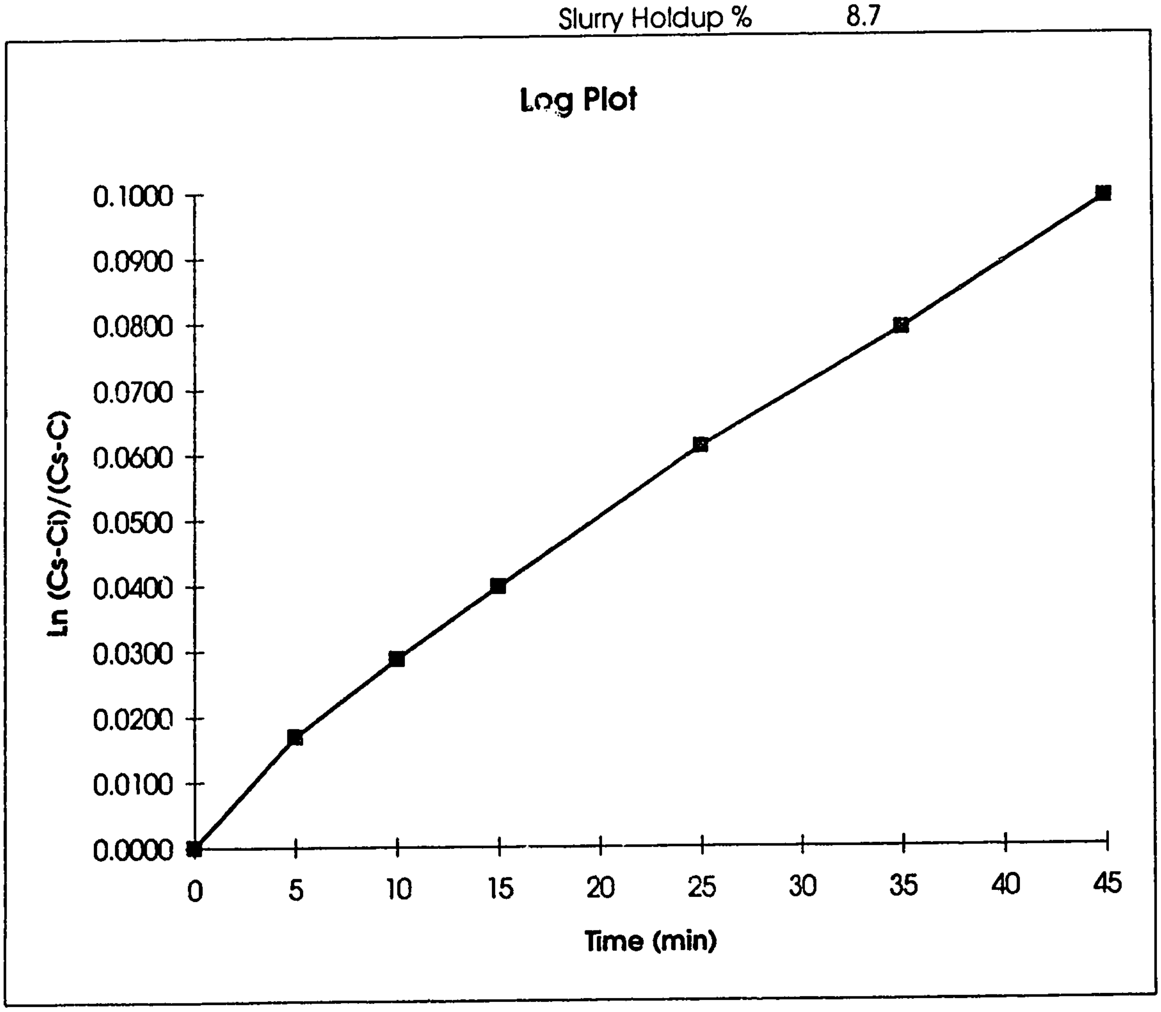
Sand and water pre-mixed for 10 minutes

Surface Area	2.19E-03 m2
Liquid Volume	1.00E-03 m3
Solid Volume	7.55E-04 m3
Total Volume	1.76E-03 m3

Ks = 1.75E-05 m/s

svf = 0.43

Slurry Holdup % 8.7



Slurry Holdup Varying Set of Data

RUN 8 Nov 30/93 Sand and Naphthol

R.P.M.	3.07	Size	425-500 micron		
Cs (g/l)	0.74	4 Baffles			
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)	
1	0	0.068	0.00[illegible]	0.0000	
2	5	0.140	0.0145	0.0100	
3	10	0.182	0.0188	0.0160	
4	15	0.220	0.0227	0.0214	
5	25	0.300	0.0308	0.0327	
6	35	0.373	0.0382	0.0432	
7	45	0.451	0.0462	0.0547	

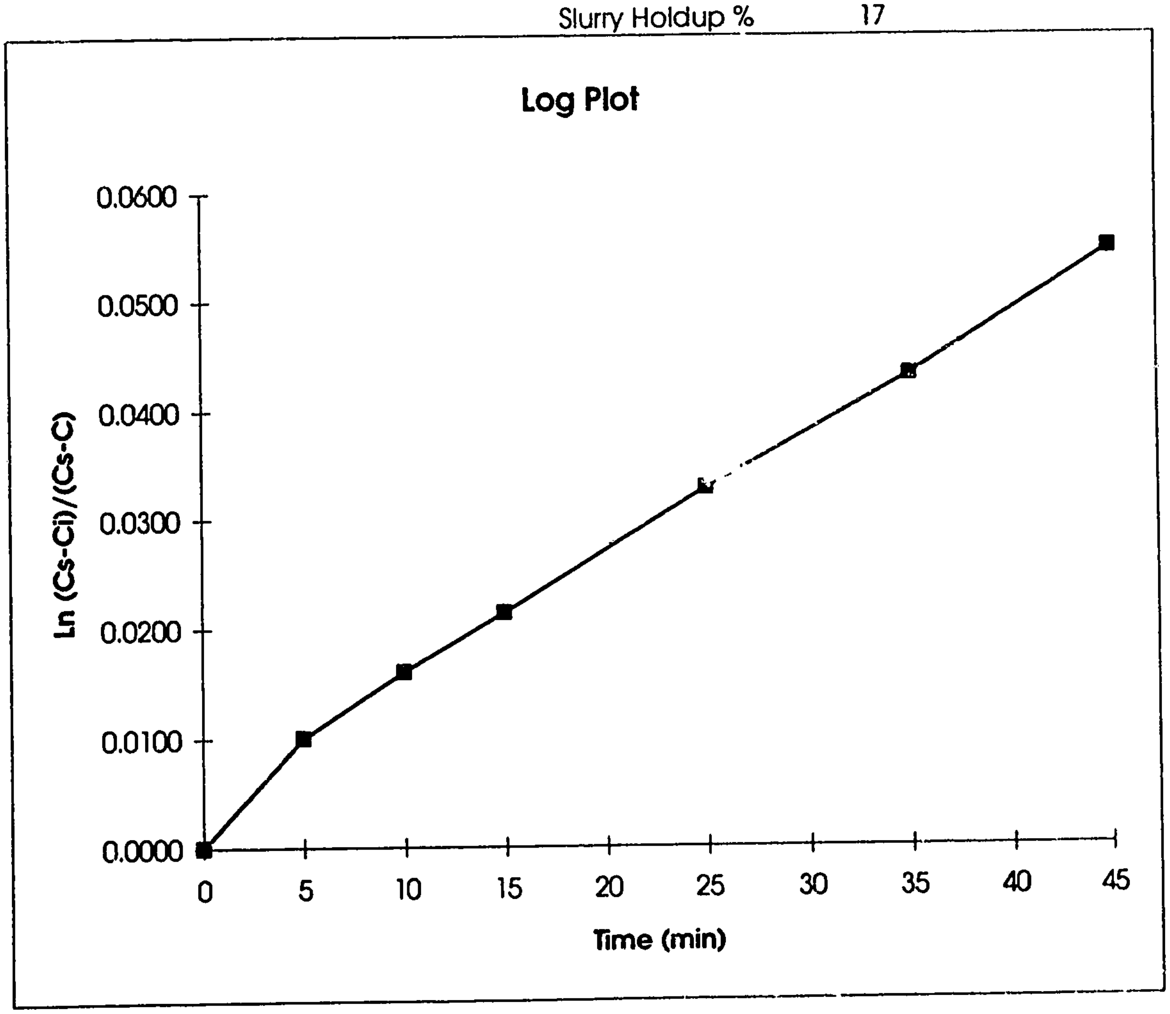
Regression	
0.00126	0
3.85E-05	#N/A
0.983073	0.002501
348.4613	6
0.002179	3.75E-05

Sand	4002.56 g	Surface Area	2.21E-03 m2
Water	2000.67 g	Liquid Volume	2.00E-03 m3
Naphthol	0.2073 g	Solid Volume	1.51E-03 m3
Sand and water pre-mixed for 10 minutes		Total Volume	3.51E-03 m3

Ks = 1.90E-05 m/s

svf = 0.43

Slurry Holdup % 17



Slurry Holdup Varying Set of Data

RUN 9 Dec 14/93 Sand and Naphthol

R.P.M. 3.07 Size 425-500 micron

Cs (g/l) 0.74 4 Baffles

Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)
1	0	0.067	0.0071	0.0000
2	5	0.347	0.0356	0.0397
3	10	0.414	0.0424	0.0494
4	15	0.446	0.0457	0.0541
5	25	0.614	0.0627	0.0789
6	35	0.722	0.0737	0.0953
7	45	0.836	0.0853	0.1128

Regression	
0.002814	0
0.000245	#N/A
0.821912	0.01592
27.69126	6
0.007018	0.001521

Sand	1005.01	g
Water	502.06	g
Naphthol	0.2042	g

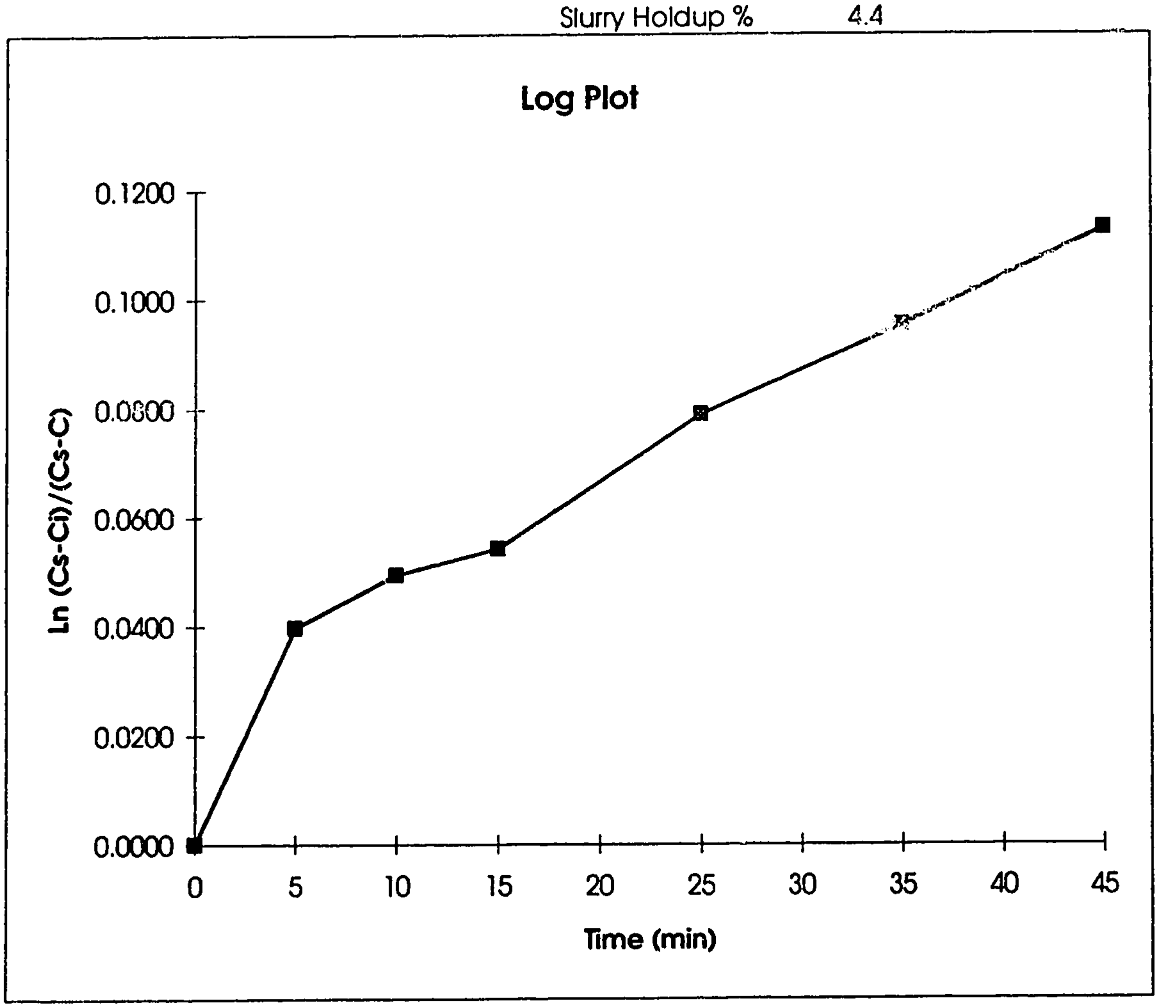
Sand and water pre-mixed for 10 minutes

Surface Area	2.18E-03	m2
Liquid Volume	5.03E-04	m3
Solid Volume	3.79E-04	m3
Total Volume	8.82E-04	m3

Ks = 1.08E-05 m/s

svf = 0.43

Slurry Holdup % 4.4



Slurry Holdup Varying Set of Data

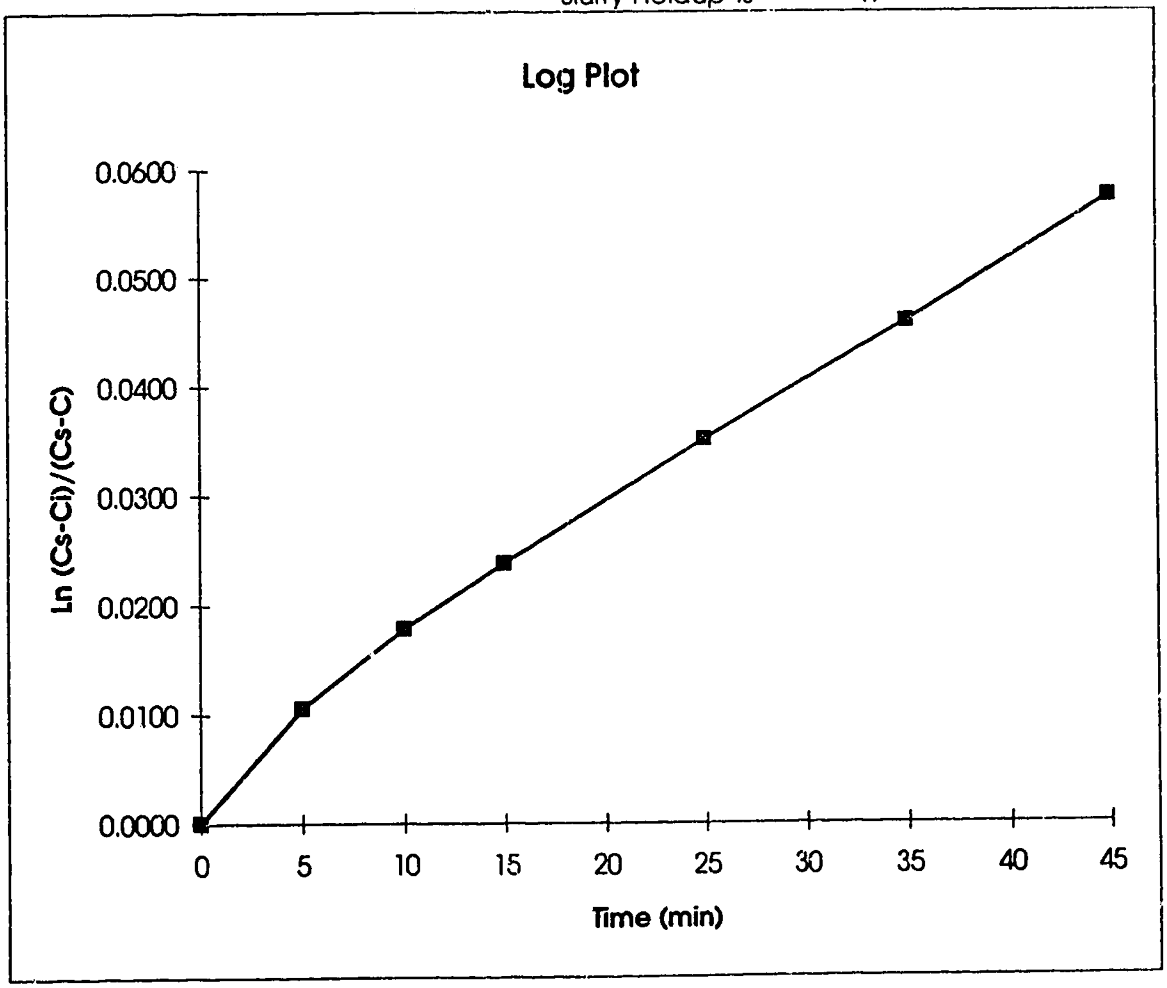
RUN 10	Dec 14/93	Sand and Naphthol				
R.P.M.	3.01	Size	425-500 micron			
Cs (g/l)	0.74	4 Baffles				
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)	Regression	
1	0	0.069	0.0073	0.0000	0.001339	0
2	5	0.144	0.0150	0.0106	4.83E-05	#N/A
3	10	0.195	0.0202	0.0178	0.975834	0.003139
4	15	0.238	0.0245	0.0238	242.2791	6
5	25	0.318	0.0326	0.0351	0.002387	5.91E-05
6	35	0.392	0.0402	0.0459		
7	45	0.471	0.0482	0.0574		

Sand	4000.5 g	Surface Area	2.42E-03 m2
Water	2006.39 g	Liquid Volume	2.01E-03 m3
Naphthol	0.2266 g	Solid Volume	1.51E-03 m3
Sand and water pre-mixed for 10 minutes		Total Volume	3.52E-03 m3

Ks = 1.86E-05 m/s

svf = 0.43

Slurry Holdup % 17



Slurry Holdup Varying Set of Data

RUN 11 Jan 7/94 Sand and Naphthol

R.P.M. 2.95 Size 425-500 micron

Cs (g/l) 0.74 4 Baffles

Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)
1	0	0.053	0.0057	0.0000
2	5	0.135	0.0140	0.0114
3	10	0.181	0.0187	0.0179
4	15	0.228	0.0235	0.0245
5	25	0.309	0.0317	0.0360
6	35	0.384	0.0393	0.0468
7	45	0.462	0.0473	0.0583

Regression

0.001365	0
5.22E-05	#N/A
0.972508	0.003394
212.2478	6
0.002445	6.91E-05

Sand	3502.12 g
Water	1753.26 g
Naphthol	0.2133 g

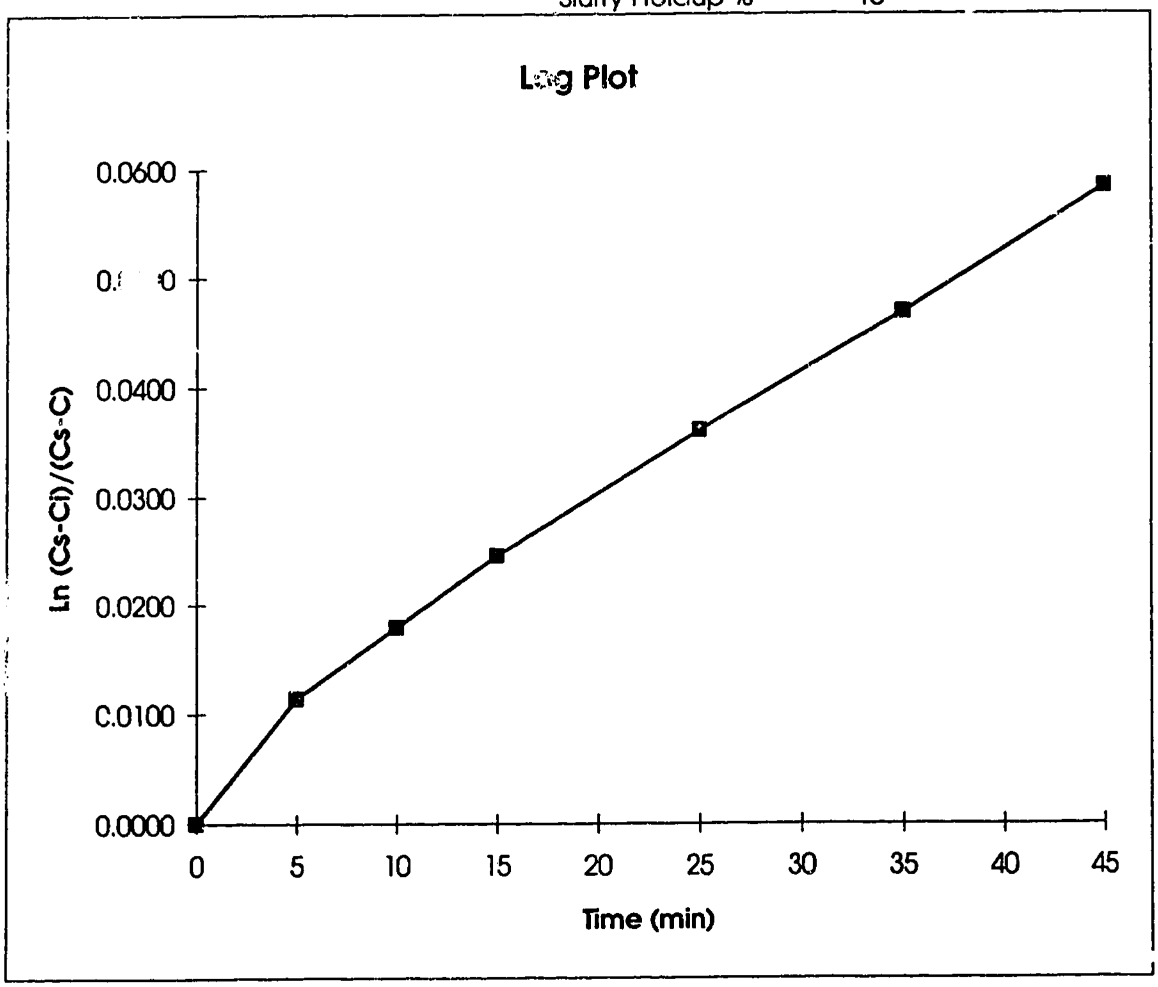
Sand and water pre-mixed for 10 minute

Surface Area	2.27E-03 m2
Liquid Volume	1.76E-03 m3
Solid Volume	1.32E-03 m3
Total Volume	3.08E-03 m3

Ks = 1.76E-05 m/s

svf = 0.43

Slurry Holdup % 15



Slurry Holdup Varying Set of Data

RUN 12 Jan 10/94 Sand and Naphthol

R.P.M. 3.02 Size 425-500 micron

Cs (g/l) 0.74 4 Baffles

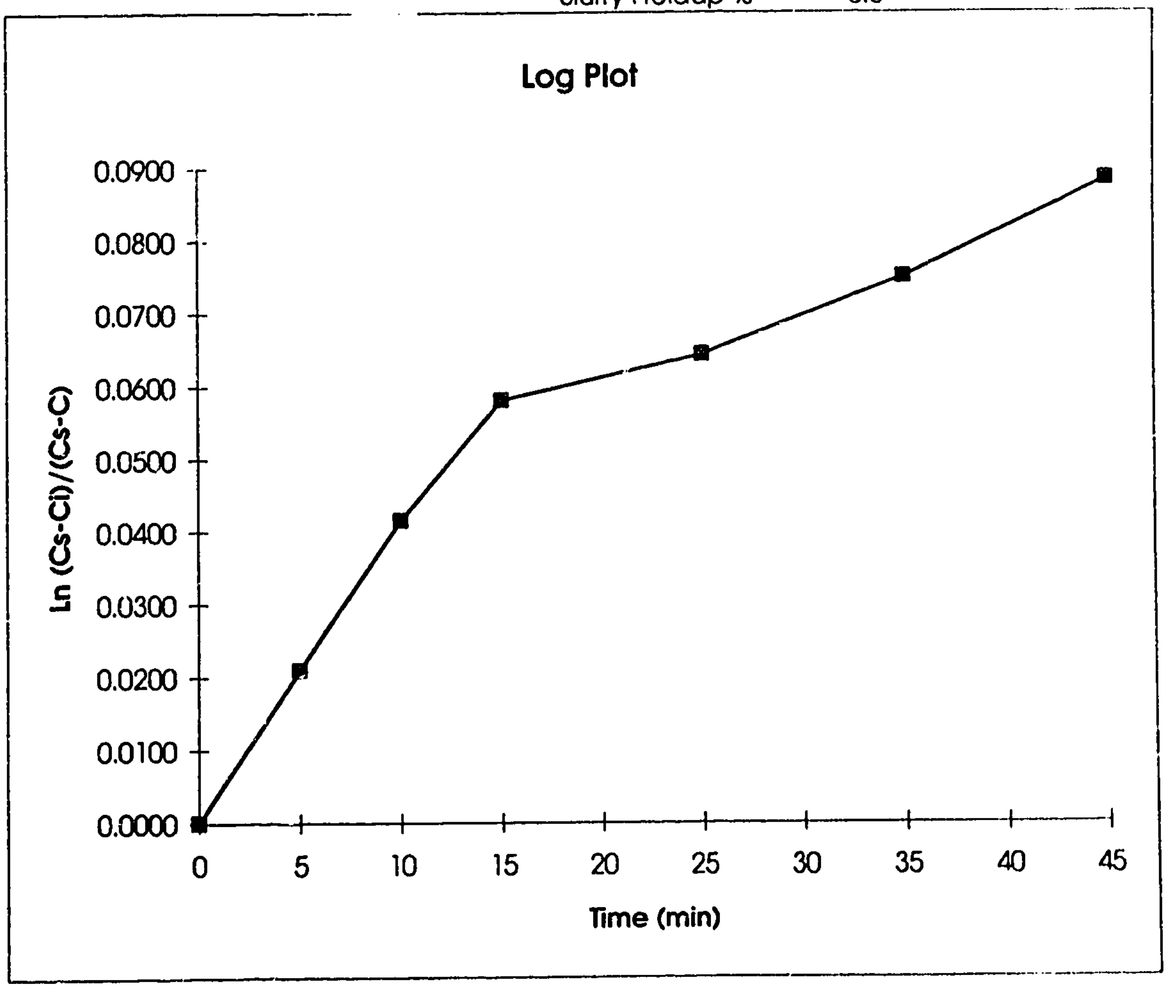
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)	Regression	
1	0	0.076	0.0081	0.0000	0.002272	0
2	5	0.227	0.0233	0.0210	0.000226	#N/A
3	10	0.370	0.0379	0.0416	0.775745	0.01469
4	15	0.483	0.0494	0.0581	20.7553	6
5	25	0.525	0.0537	0.0643	0.004479	0.001295
6	35	0.596	0.0609	0.0749		
7	45	0.686	0.0700	0.0884		

Sand	1499.22 g	Surface Area	2.15E-03 m2
Water	752.27 g	Liquid Volume	7.54E-04 m3
Naphthol	0.2021 g	Solid Volume	5.66E-04 m3
Sand and water pre-mixed for 10 minutes		Total Volume	1.32E-03 m3

Ks = 1.32E-05 m/s

svf = 0.43

Slurry Holdup % 6.6



Slurry Holdup Varying Set of Data

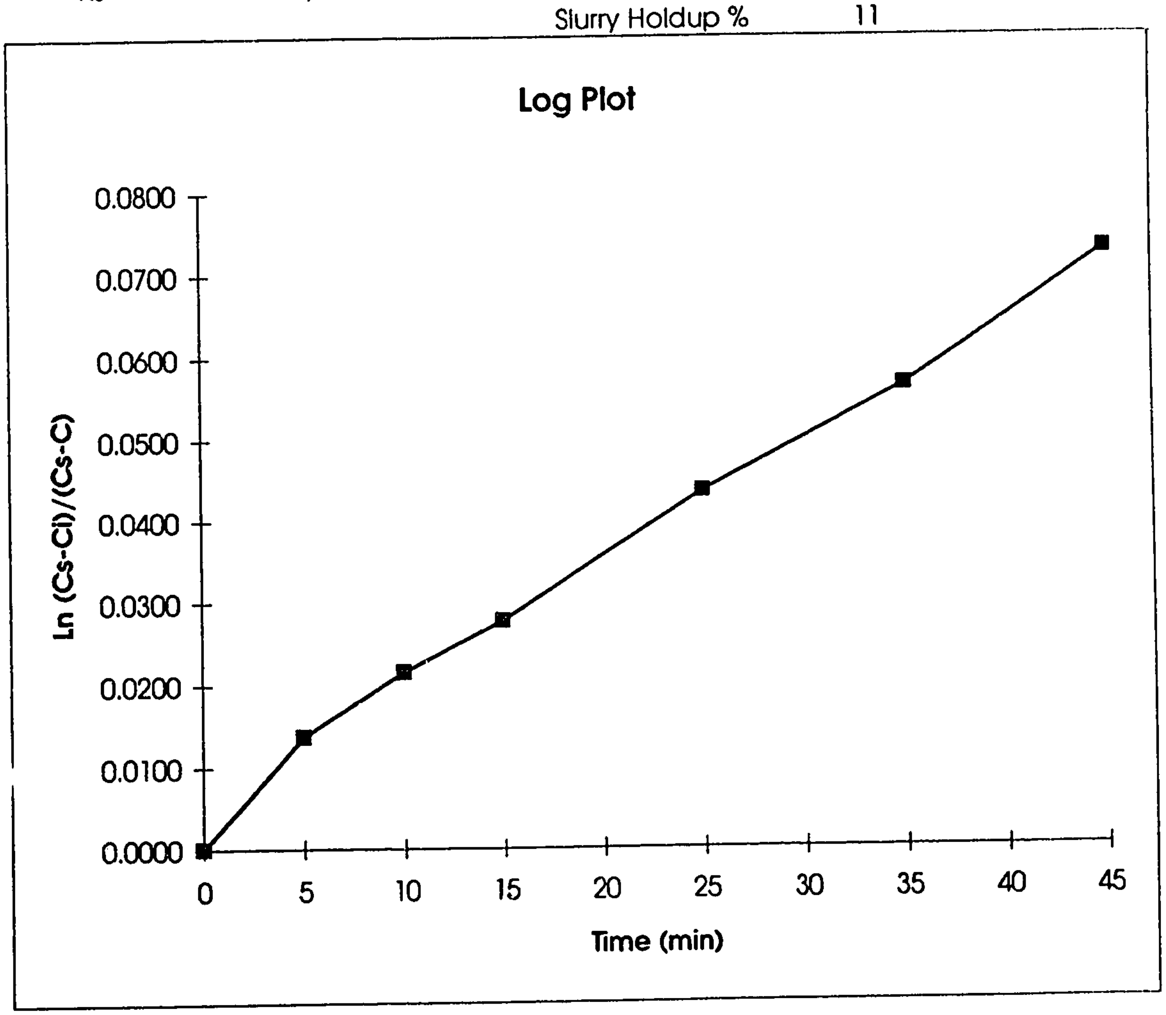
RUN 13	Jan 12/94	Sand and Naphthol					
R.P.M.	3.05	Size	425-500 micron				
Cs (g/l)	0.74	4 Baffles					
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)		Regression	
1	0	0.079	0.0084	0.0000		0.001667	0
2	5	0.178	0.0184	0.0138		5.32E-05	#N/A
3	10	0.233	0.0240	0.0216		0.981411	0.00346
4	15	0.276	0.0284	0.0277		316.7727	6
5	25	0.385	0.0395	0.0434		0.003793	7.18E-05
6	35	0.475	0.0486	0.0565			
7	45	0.585	0.0598	0.0728			

Sand	2499.09 g	Surface Area	2.21E-03 m2
Water	1252.37 g	Liquid Volume	1.25E-03 m3
Naphthol	0.2069 g	Solid Volume	9.43E-04 m3
Sand and water pre-mixed for 10 minutes		Total Volume	2.20E-03 m3

Ks = 1.58E-05 m/s

svf = 0.43

Slurry Holdup % 11



Slurry Holdup Varying Set of Data

RUN 14 Jan 14/94 Sand and Naphthol

R.P.M. 3.08 Size 425-500 micron

Cs (g/l) 0.74 4 Baffles

Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)
1	0	0.076	0.0080	0.0000
2	5	0.166	0.0172	0.0126
3	10	0.218	0.0225	0.0200
4	15	0.281	0.0289	0.0290
5	25	0.365	0.0374	0.0410
6	35	0.480	0.0491	0.0578
7	45	0.550	0.0562	0.0681

Regression

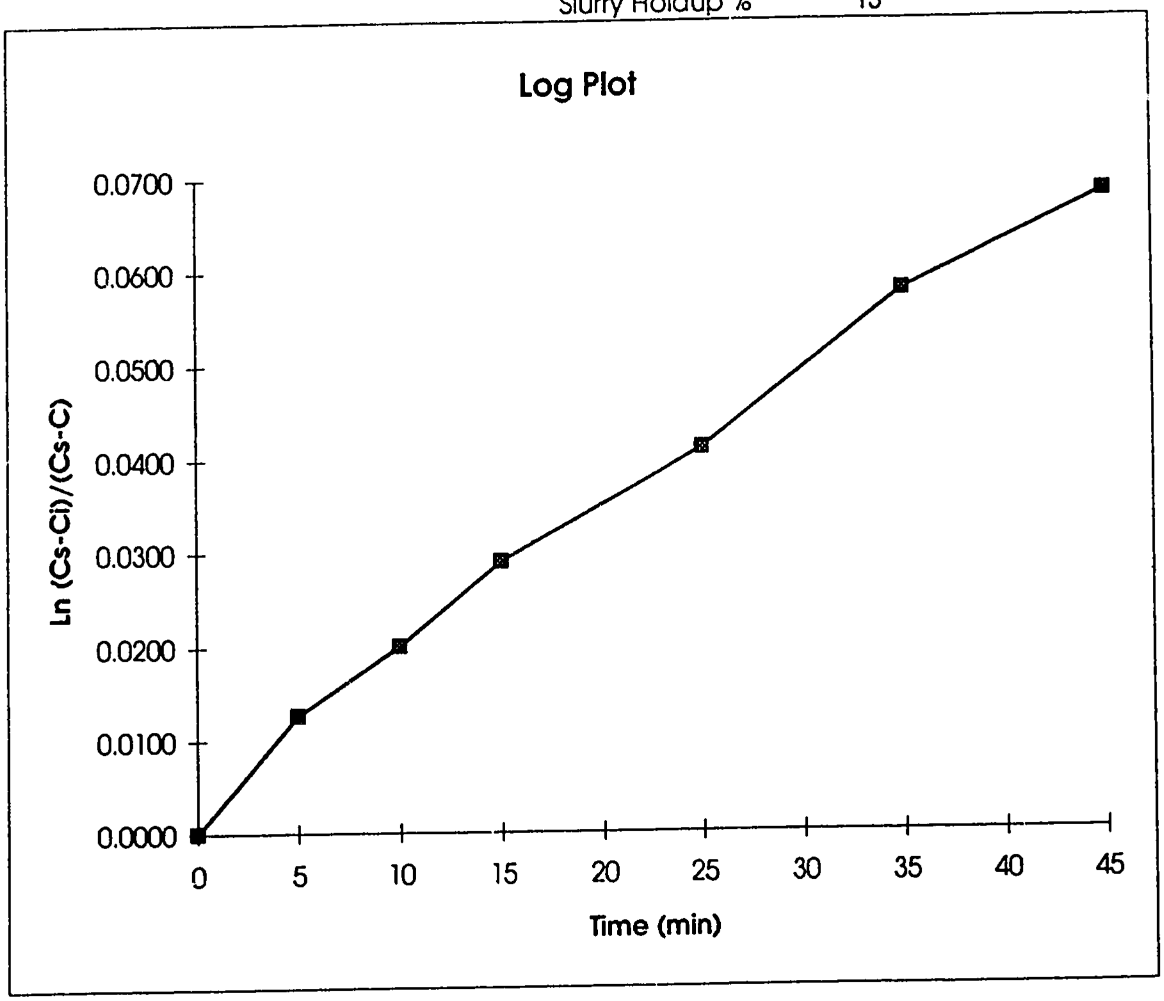
0.001612	0
5.65E-05	#N/A
0.97749	0.003674
260.545	6
0.003518	8.1E-05

Sand 2995.9 g
Water 1501.04 g
Naphthol 0.2205 g
Sand and water pre-mixed for 10 minutes

Surface Area 2.35E-03 m2
Liquid Volume 1.50E-03 m3
Solid Volume 1.13E-03 m3
Total Volume 2.63E-03 m3

Ks = 1.72E-05 m/s

svf = 0.43
Slurry Holdup % 13



Solids Volume Fraction Varying Set of Data

RUN 1 March 3/9: Sand and Naphthol

R.P.M. 3.00 Size 425-500 micron

Cs 0.74 4 Baffles

Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)
1	0	0.047	0.0051	0.0000
2	5	0.203	0.0209	0.0217
3	10	0.250	0.0257	0.0284
4	15	0.269	0.0276	0.0311
5	25	0.370	0.0379	0.0457
6	35	0.459	0.0470	0.0587
7	45	0.534	0.0546	0.0697

Regression	
0.001703	0
0.000125	#N/A
0.881683	0.008098
44.71113	6
0.002932	0.000394

Check to see is all surfactant is removed, compare results to other runs of 2 kg sand, 1 kg water, and 3 rpm.

Sand	2002.58 g
Water	1000.27 g
Naphthol	0.2339 g

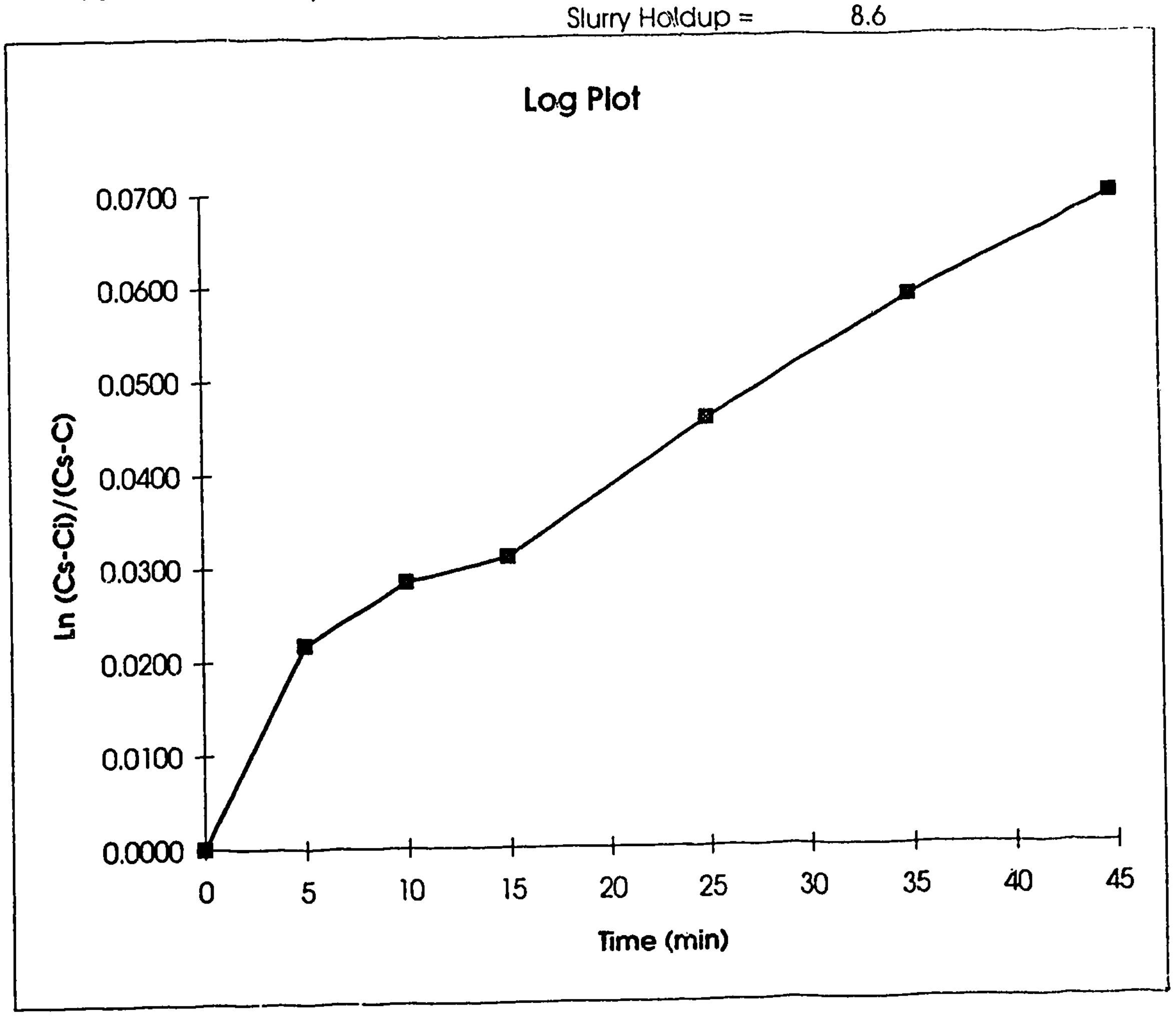
Sand and water pre-mixed for 10 minutes

Surface Area	2.49E-03 m2
Liquid Volume	1.00E-03 m3
Solid Volume	7.56E-04 m3
Total Volume	1.76E-03 m3

Ks = 1.14E-05 m/s

svf = 0.43

Slurry Holdup = 8.6



Solids Volume Fraction Varying Set of Data

RUN 2 March 3/9: Sand and Naphthol

R.P.M.	3.08	Size	425-500 micron			
Cs	0.74	4 Baffles				
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)	Regression	
1	0	0.021	0.0025	0.0000	0.001196	0
2	5	0.084	0.0089	0.0087	3.49E-05	#N/A
3	10	0.130	0.0135	0.0150	0.984727	0.002267
4	15	0.170	0.0176	0.0207	386.856	6
5	25	0.242	0.0249	0.0308	0.001989	3.08E-05
6	35	0.318	0.0327	0.0418		
7	45	0.386	0.0395	0.0515		

Sand	0	g
Water	1768.28	g
Naphthol	0.2070	g

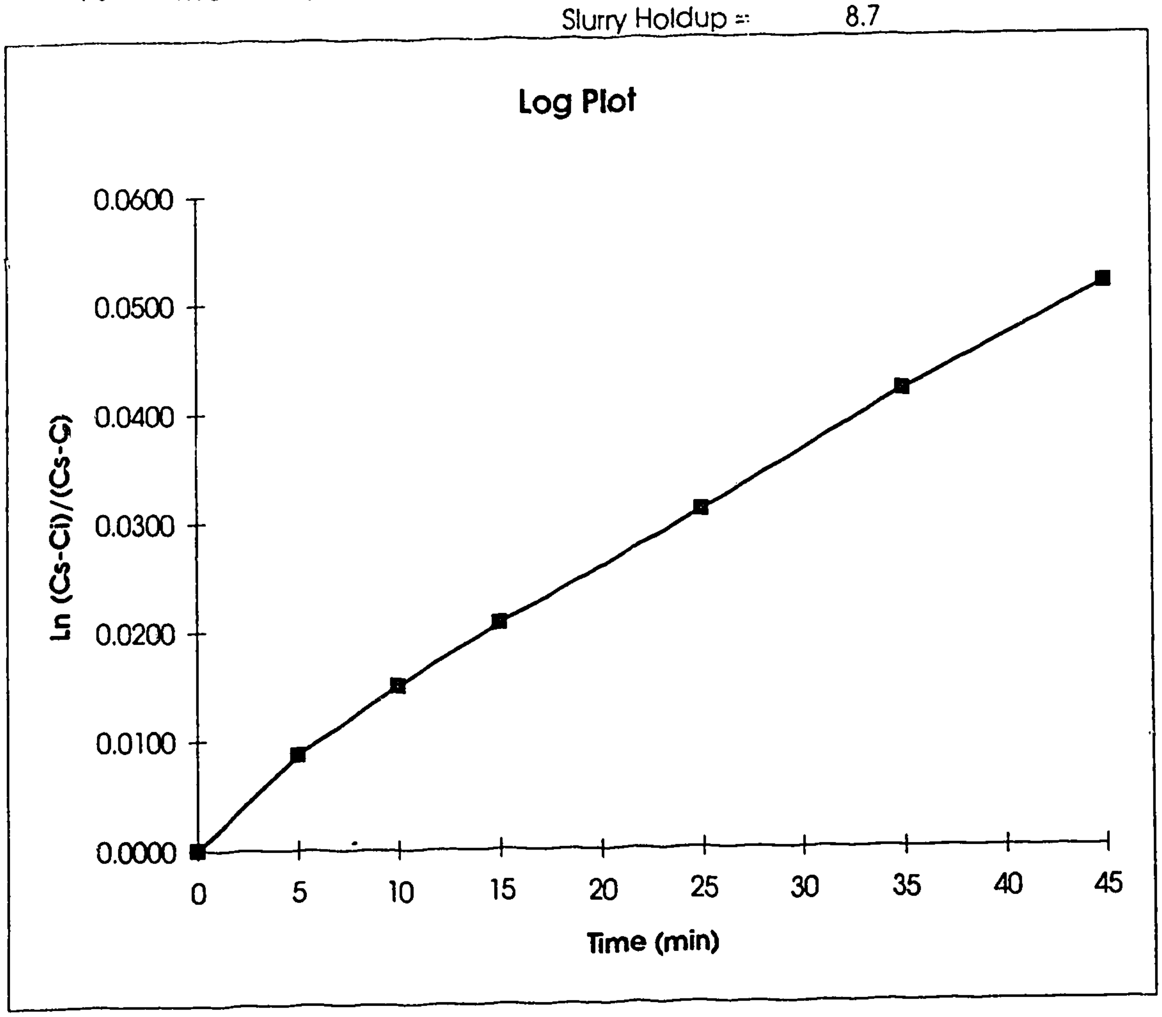
Sand and water pre-mixed for 10 minutes

Surface Area	2.21E-03	m2
Liquid Volume	1.77E-03	m3
Solid Volume	0.00E+00	m3
Total Volume	1.77E-03	m3

Ks = 1.60E-05 m/s

svf = 0.00

Slurry Holdup = 8.7



Solids Volume Fraction Varying Set of Data

RUN 3 March 4/9? Sand and Naphthol

R.P.M. 3.03 Size 425-500 micron

Cs 0.74 4 Baffles

Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)
1	0	0.042	0.0046	0.0000
2	5	0.153	0.0159	0.0155
3	10	0.179	0.0185	0.0191
4	15	0.228	0.0235	0.0260
5	25	0.302	0.0310	0.0366
6	35	0.376	0.0386	0.0473
7	45	0.449	0.0459	0.0578

Regression

0.00138	0
7.79E-05	#N/A
0.934669	0.005062
85.84018	6
0.0022	0.000154

Sand 1404.55 g

Water 1234.72 g

Naphthol 0.2084 g

Sand and water pre-mixed for 10 minutes

Surface Area 2.22E-03 m2

Liquid Volume 1.24E-03 m3

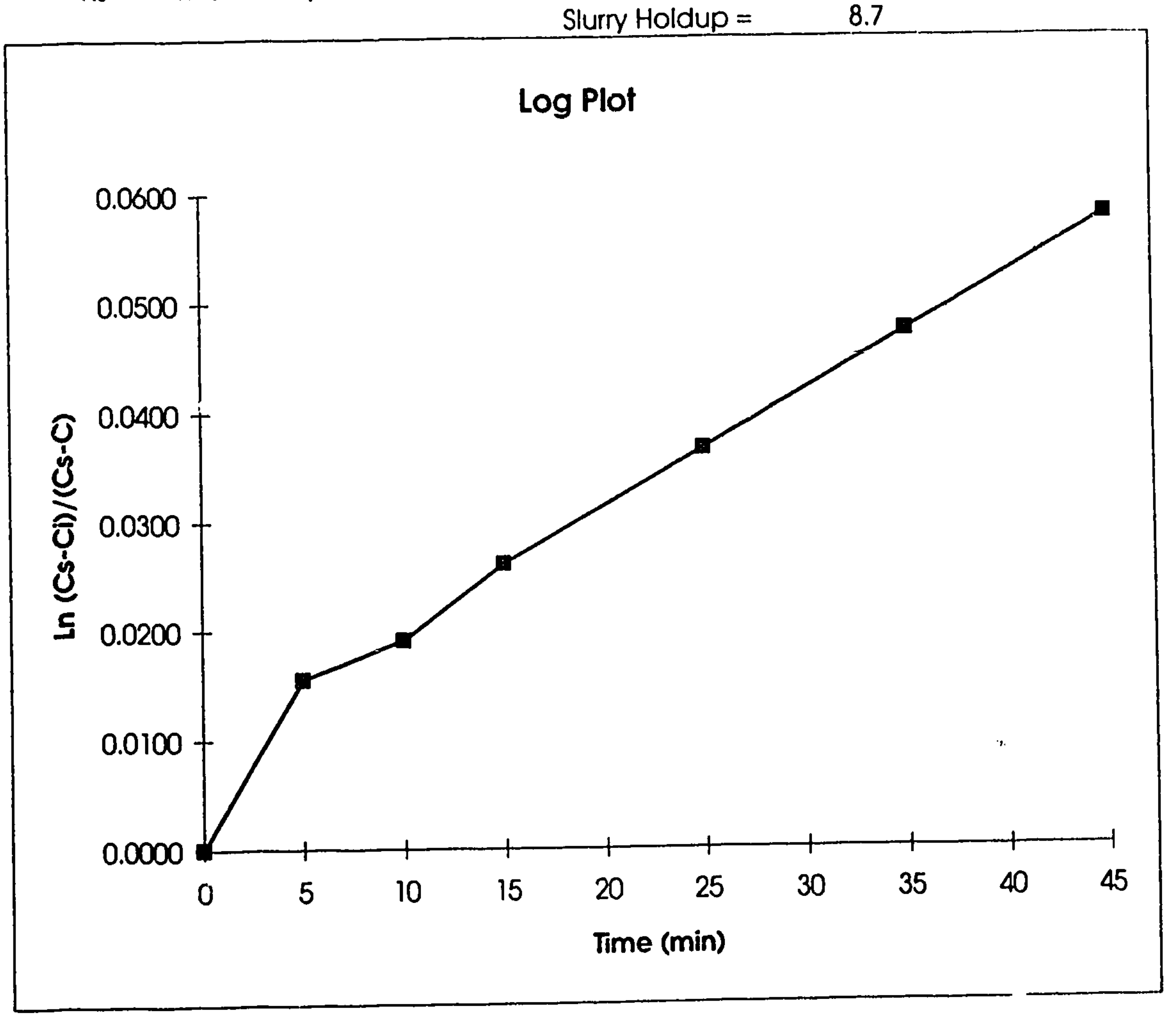
Solid Volume 5.30E-04 m3

Total Volume 1.77E-03 m3

Ks = 1.28E-05 m/s

svf = 0.30

Slurry Holdup = 8.7



Solids Volume Fraction Varying Set of Data

RUN 4 March 4/9: Sand and Naphthol

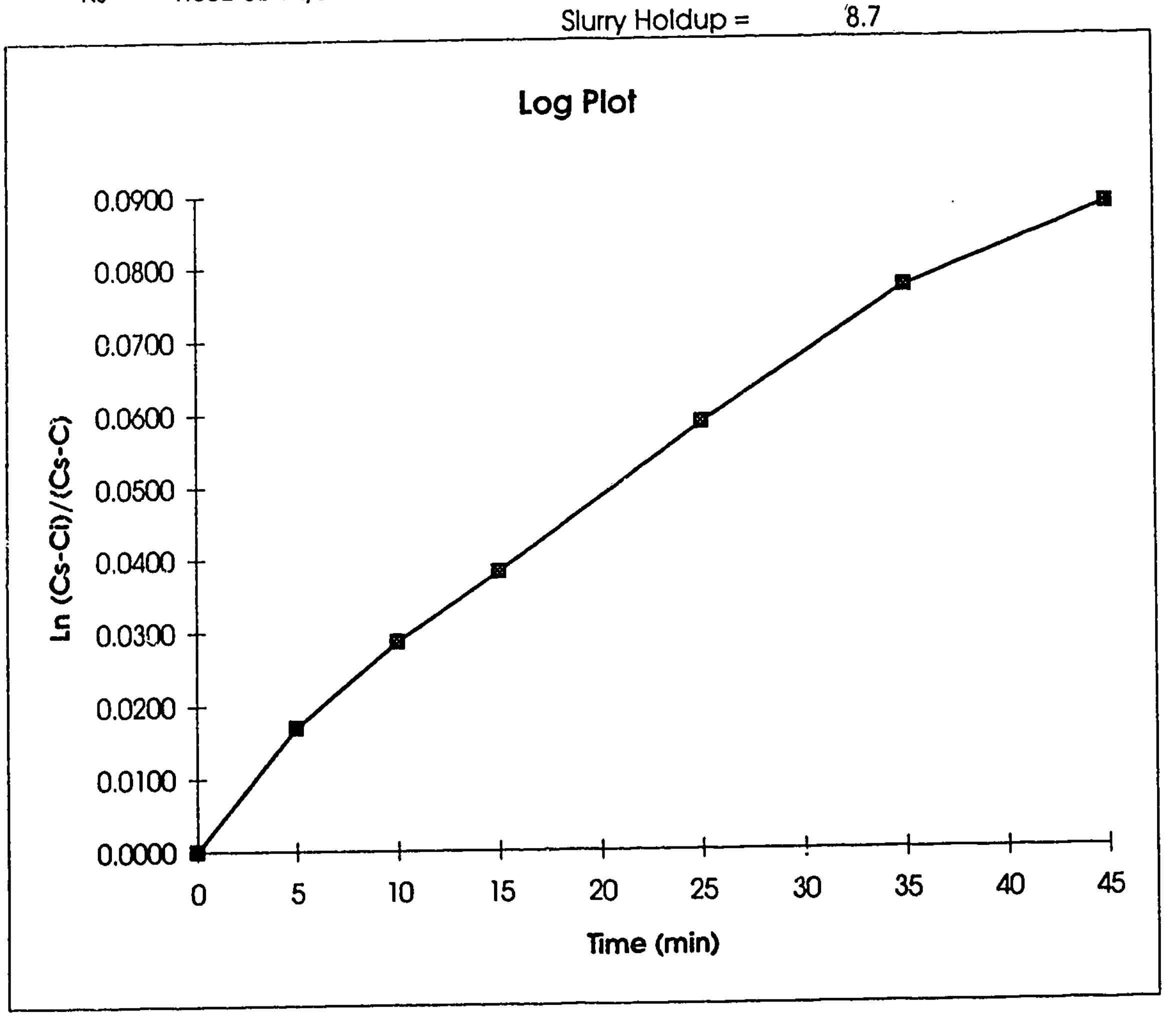
R.P.M.	2.99	Size	425-500 micron				
Cs	0.74	4 Baffles					
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)		Regression	
1	0	0.073	0.0077	0.0000		0.00215	0
2	5	0.194	0.0200	0.0169		9.41E-05	#N/A
3	10	0.276	0.0284	0.0287		0.963864	0.006114
4	15	0.344	0.0352	0.0383		160.0376	6
5	25	0.483	0.0494	0.0586		0.005981	0.000224
6	35	0.607	0.0620	0.0770			
7	45	0.682	0.0696	0.0883			

Sand	2262.80 g	Surface Area	2.16E-03 m2
Water	904.80 g	Liquid Volume	9.06E-04 m3
Naphthol	0.2027 g	Solid Volume	8.54E-04 m3
Sand and water pre-mixed for 10 minutes		Total Volume	1.76E-03 m3

Ks = 1.50E-05 m/s

svf = 0.49

Slurry Holdup = 8.7



Solids Volume Fraction Varying Set of Data

RUN 5 March 5/9: Sand and Naphthol

R.P.M. 3.00 Size 425-500 micron

Cs 0.74 4 Baffles

Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)
1	0	0.062	0.0066	0.0000
2	5	0.214	0.0221	0.0214
3	10	0.364	0.0373	0.0428
4	15	0.671	0.0685	0.0882
5	25	0.547	0.0559	0.0696
6	35	1.492	0.1519	0.2208
7	45	1.066	0.1086	0.1498

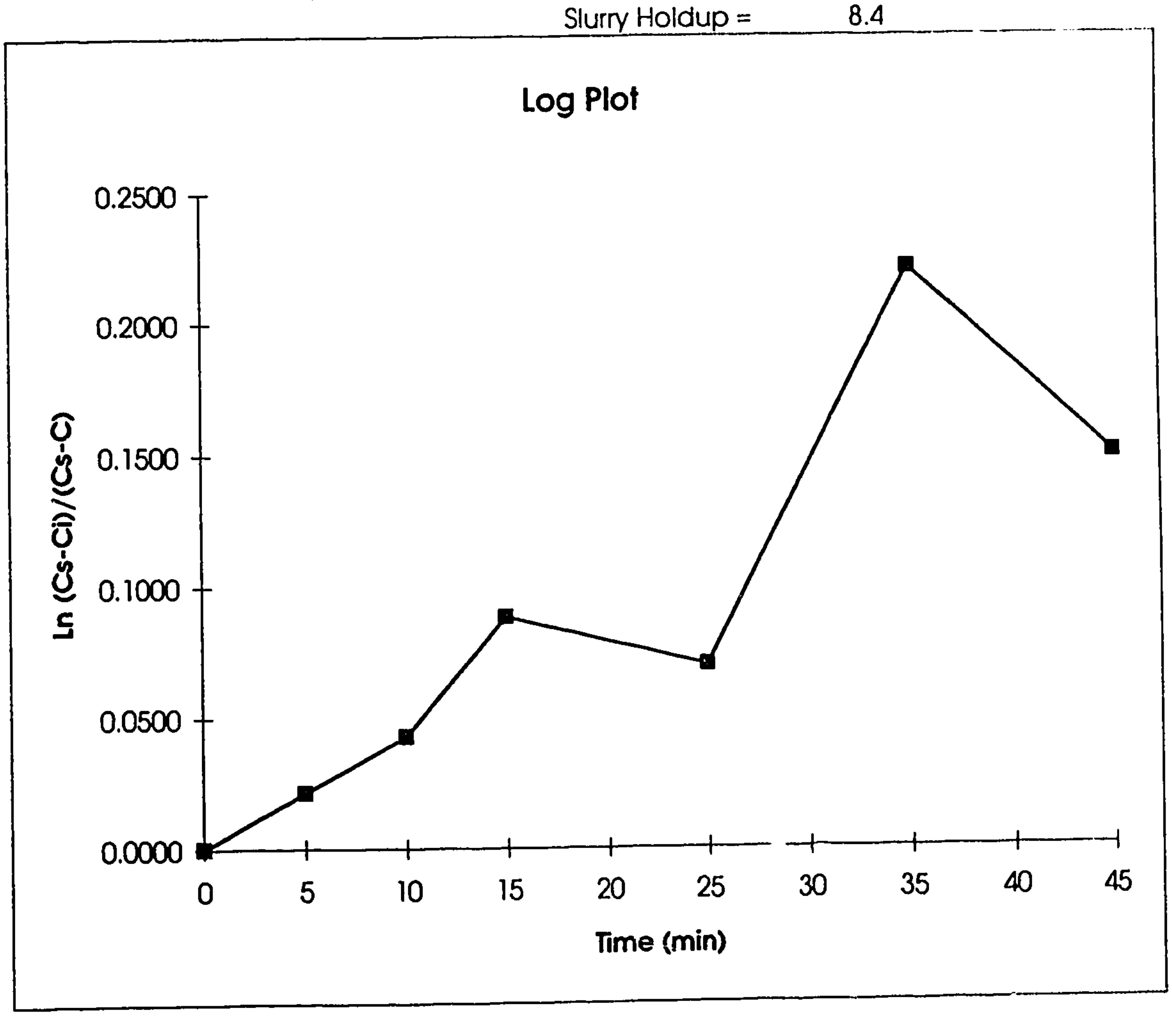
Regression	
0.004275	0
0.000591	#N/A
0.753727	0.038407
18.36322	6
0.027088	0.008851

Sand 2807.67 g
Water 657.44 g
Naphthol 0.2225 g
Sand and water pre-mixed for 10 minutes

Surface Area 2.37E-03 m2
Liquid Volume 6.59E-04 m3
Solid Volume 1.06E-03 m3
Total Volume 1.72E-03 m3

Ks = 1.98E-05 m/s

svf = 0.62
Slurry Holdup = 8.4



Solids Volume Fraction Varying Set of Data

RUN 6 March 5/9: Sand and Naphthol

R.P.M. 3.02 Size 425-500 micron

Cs 0.74 4 Baffles

Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)
1	0	0.035	0.0039	0.0000
2	5	0.092	0.0097	0.0079
3	10	0.144	0.0149	0.0151
4	15	0.184	0.0190	0.0207
5	25	0.262	0.0269	0.0317
6	35	0.333	0.0342	0.0420
7	45	0.397	0.0407	0.0513

Regression

0.001201	0
3.49E-05	#N/A
0.984998	0.002267
393.9384	6
0.002024	3.08E-05

Sand	701.40 g
Water	1505.40 g
Naphthol	0.2092 g

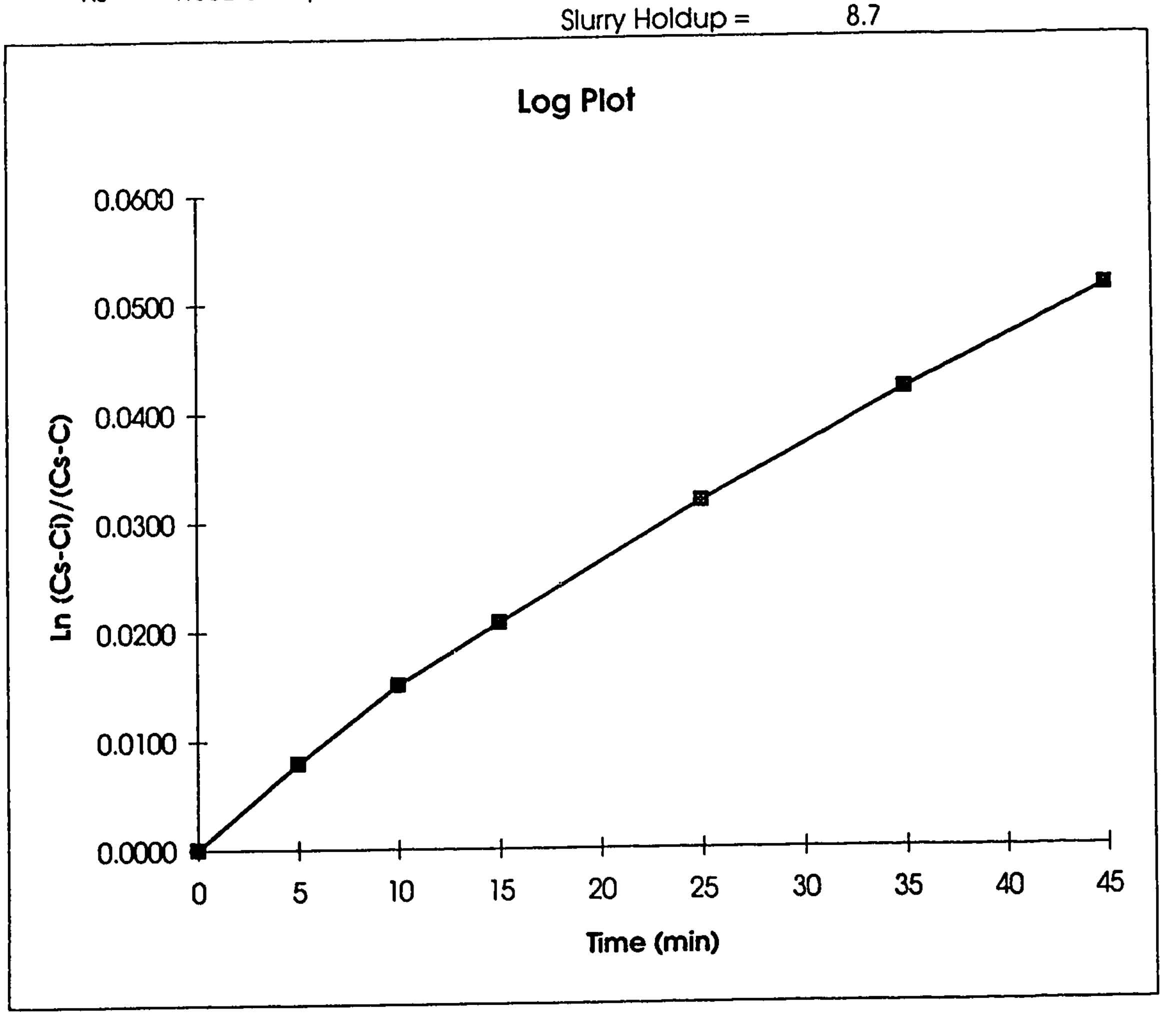
Sand and water pre-mixed for 10 minutes

Surface Area	2.23E-03 m2
Liquid Volume	1.51E-03 m3
Solid Volume	2.65E-04 m3
Total Volume	1.77E-03 m3

Ks = 1.35E-05 m/s

svf = 0.15

Slurry Holdup = 8.7



Solids Volume Fraction Varying Set of Data

RUN 7 March 23/9 Sand and Naphthol

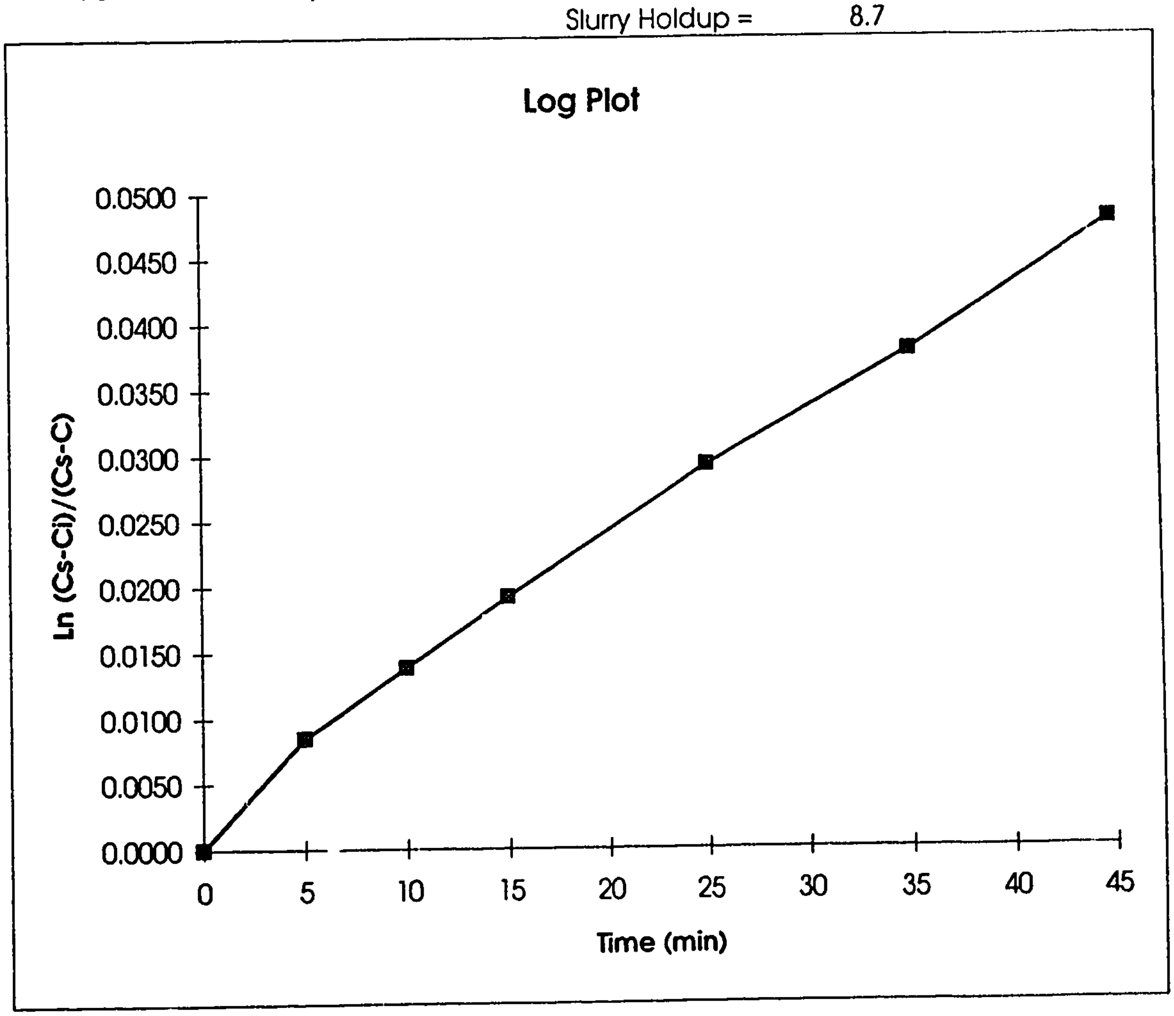
R.P.M.	3.07	Size	425-500 micron			
Cs	0.74	4 Baffles				
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)	Regression	
1	0	0.026	0.0030	0.0000	0.001106	0
2	5	0.087	0.0092	0.0084	3.42E-05	#N/A
3	10	0.125	0.0131	0.0138	0.982686	0.002223
4	15	0.164	0.0170	0.0192	340.5324	6
5	25	0.235	0.0242	0.0292	0.001682	2.96E-05
6	35	0.296	0.0304	0.0379		
7	45	0.365	0.0374	0.0478		

Sand	0.00 g	Surface Area	2.23E-03 m2
Water	1761.55 g	Liquid Volume	1.76E-03 m3
Naphthol	0.2090 g	Solid Volume	0.00E+00 m3
Sand and water pre-mixed for 10 minutes		Total Volume	1.76E-03 m3

Ks = 1.46E-05 m/s

svf = 0.00

Slurry Holdup = 8.7



Solids Volume Fraction Varying Set of Data

RUN 8 March 28/9 Sand and Naphthol

R.P.M. 3.04 Size 425-500 micron

Cs 0.74 4 Baffles

Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)
1	0	0.132	0.0137	0.0000
2	5	0.436	0.0446	0.0435
3	10	0.646	0.0660	0.0747
4	15	0.689	0.0704	0.0813
5	25	0.806	0.0822	0.0991
6	35	0.875	0.0892	0.1098
7	45	1.012	0.1031	0.1314

Regression	
0.003411	0
0.000399	#N/A
0.652427	0.025912
11.26257	6
0.007562	0.004028

Sand	2601.45 g
Water	777.66 g
Naphthol	0.2375 g

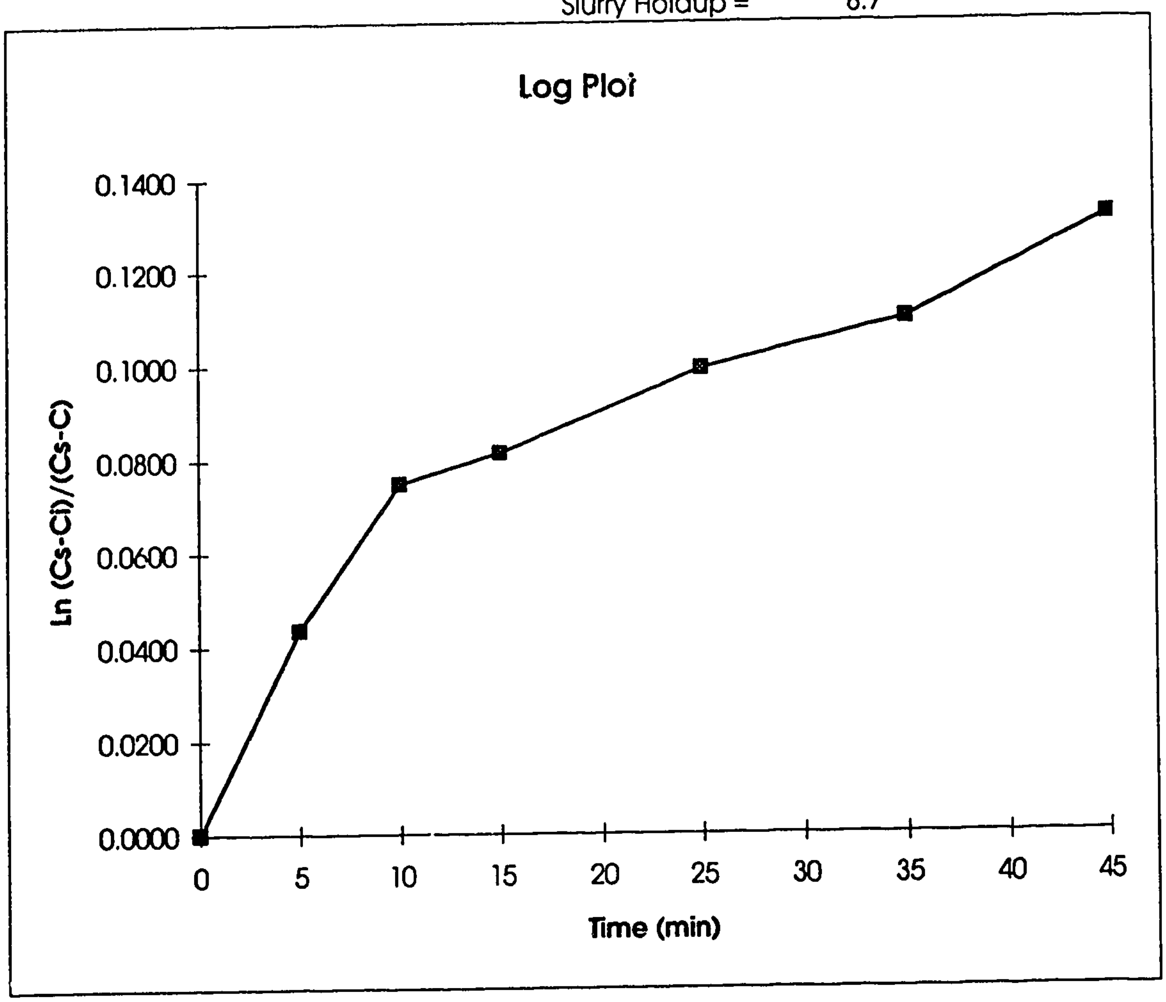
Sand and water pre-mixed for 10 minutes

Surface Area	2.53E-03 m2
Liquid Volume	7.79E-04 m3
Solid Volume	9.82E-04 m3
Total Volume	1.76E-03 m3

Ks = 1.75E-05 m/s

svf = 0.56

Slurry Holdup = 8.7



Solids Volume Fraction Varying Set of Data

RUN 9 April 5/94 Sand and Naphthol

R.P.M. 3.06 Size 425-500 micron

Cs 0.74 4 Baffles

Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)
1	0	0.110	0.0115	0.0000
2	5	0.242	0.0249	0.0186
3	10	0.330	0.0338	0.0311
4	15	0.400	0.0410	0.0413
5	25	0.530	0.0542	0.0604
6	35	0.666	0.0680	0.0807
7	45	0.771	0.0787	0.0968

Regression

0.002299	0
9.22E-05	#N/A
0.969608	0.005996
191.4227	6
0.006882	0.000216

Sand	2004.17 g
Water	1000.19 g
Naphthol	0.2038 g

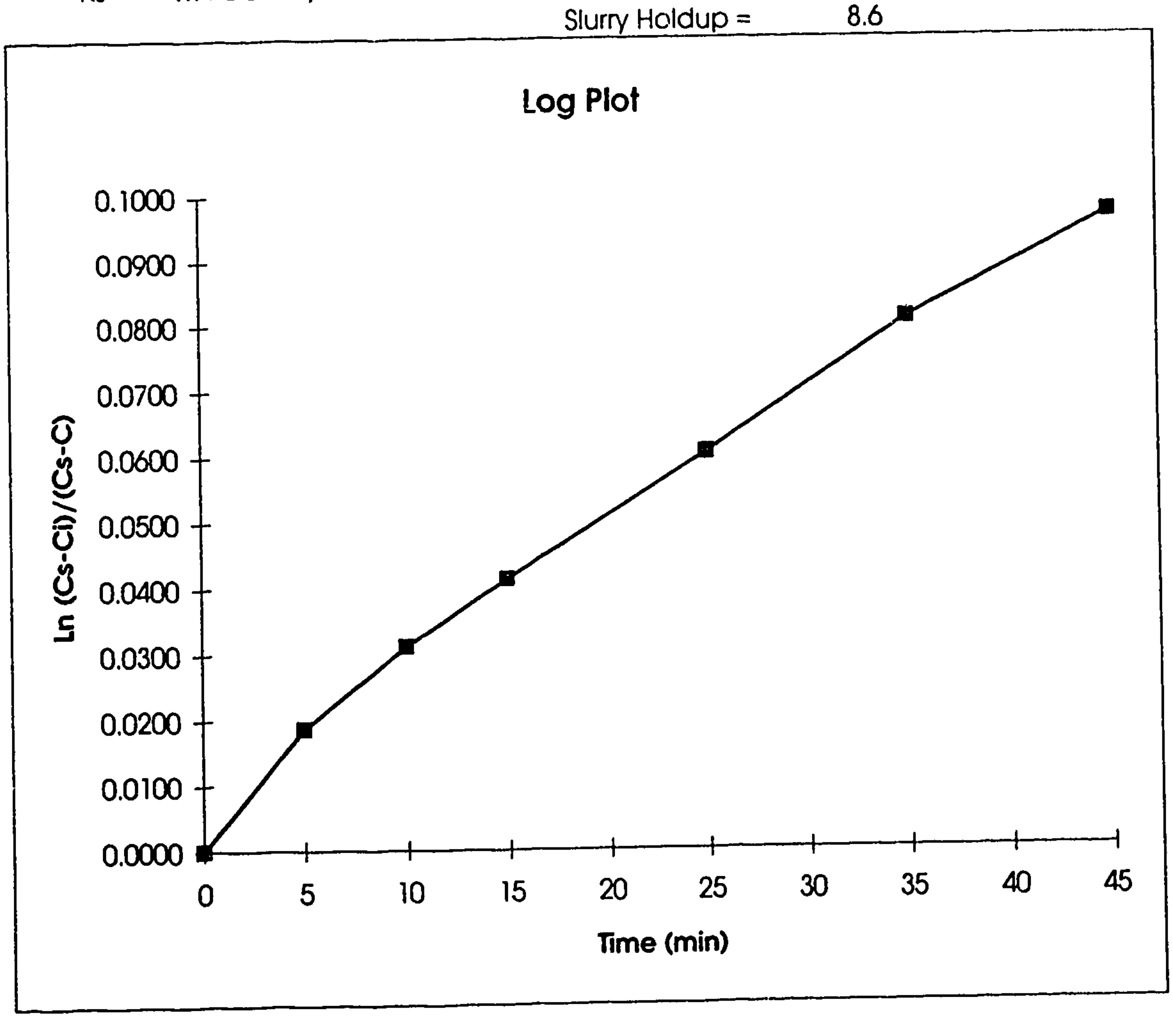
Sand and water pre-mixed for 10 minutes

Surface Area	2.17E-03 m2
Liquid Volume	1.00E-03 m3
Solid Volume	7.56E-04 m3
Total Volume	1.76E-03 m3

Ks = 1.77E-05 m/s

svf = 0.43

Slurry Holdup = 8.6



Solids Volume Fraction Varying Set of Data

RUN 10 April 7/94 Sand and Naphthol

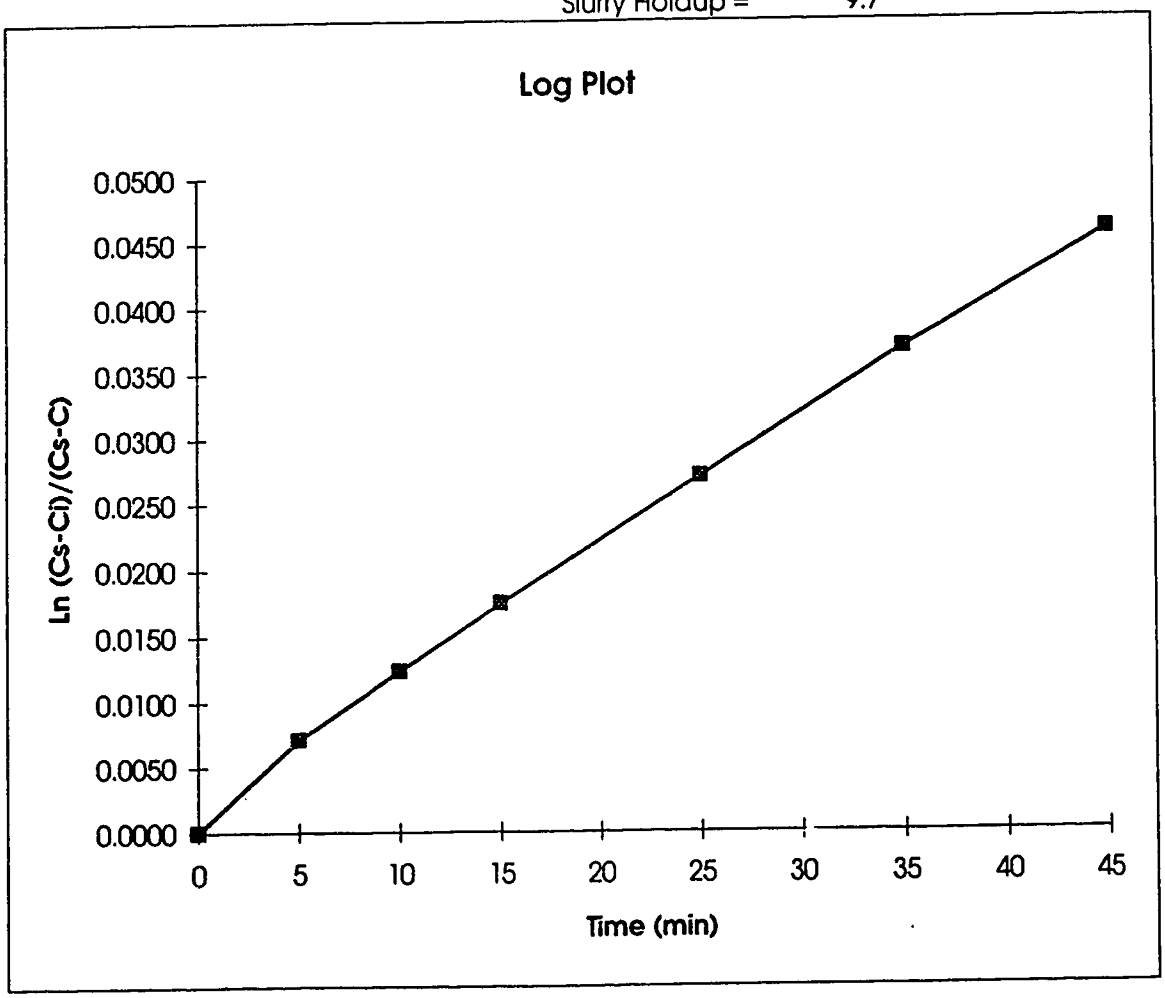
R.P.M.	3.01	Size	425-500 micron			
Cs	0.74	4 Baffles				
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)	Regression	
1	0	0.046	0.0050	0.0000	0.001052	0
2	5	0.097	0.0102	0.0071	2.2E-05	#N/A
3	10	0.135	0.0140	0.0123	0.99245	0.00143
4	15	0.171	0.0177	0.0174	788.6519	6
5	25	0.239	0.0246	0.0270	0.001613	1.23E-05
6	35	0.308	0.0316	0.0369		
7	45	0.370	0.0379	0.0458		

Sand	700.97 g	Surface Area	2.19E-03 m2
Water	1698.94 g	Liquid Volume	1.70E-03 m3
Naphthol	0.2055 g	Solid Volume	2.65E-04 m3
Sand and water pre-mixed for 10 minutes		Total Volume	1.97E-03 m3

Ks = 1.36E-05 m/s

svf = 0.13

Slurry Holdup = 9.7



Solids Volume Fraction Varying Set of Data

RUN 11 April 8/94 Sand and Naphthol

R.P.M. 2.97 Size 425-500 micron

Cs 0.74 4 Baffles

Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)
1	0	0.064	0.0068	0.0000
2	5	0.190	0.0196	0.0176
3	10	0.216	0.0223	0.0214
4	15	0.269	0.0277	0.0289
5	25	0.338	0.0347	0.0388
6	35	0.444	0.0455	0.0542
7	45	0.482	0.0493	0.0597

Regression

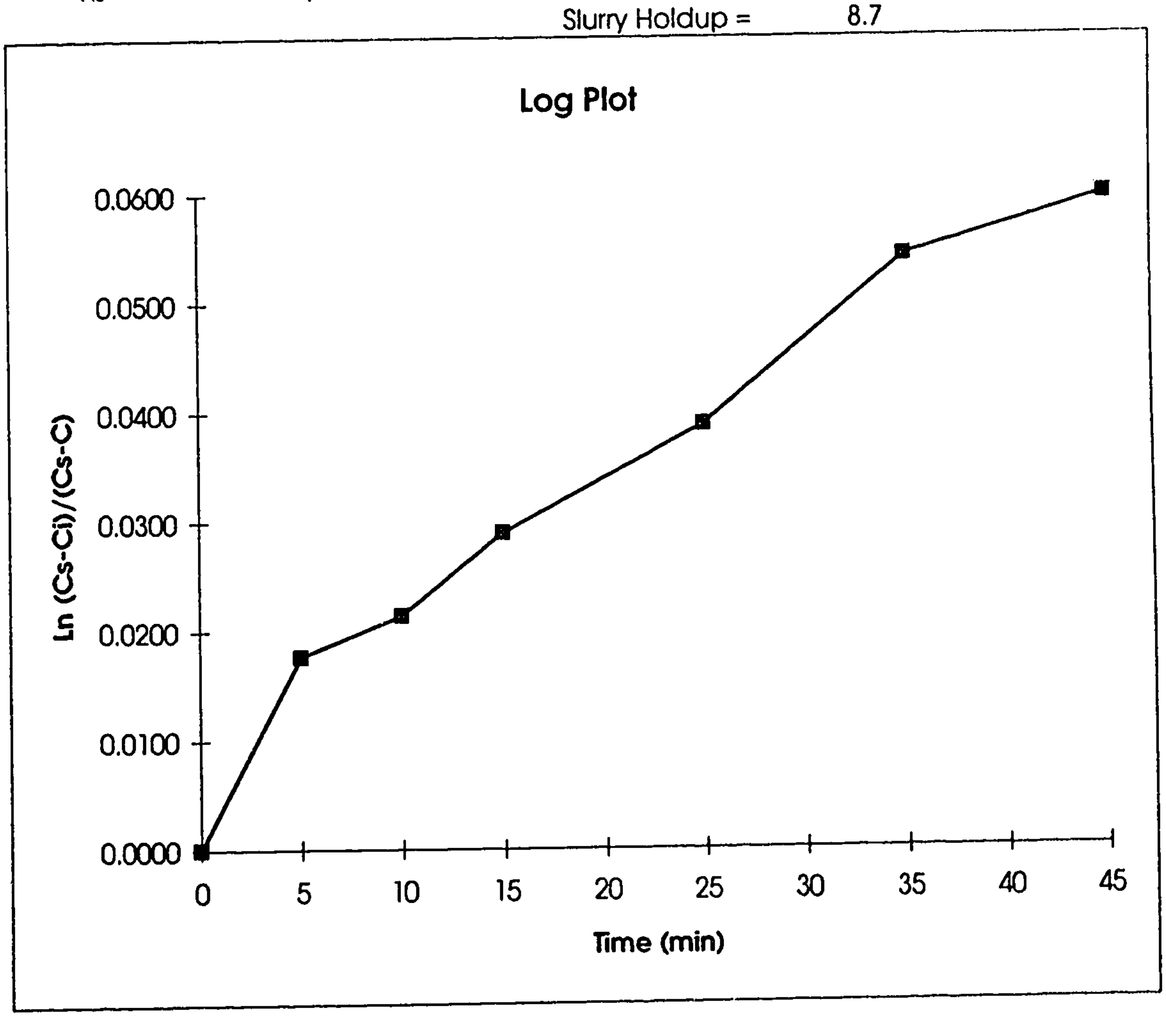
0.001489	0
9.91E-05	#N/A
0.906484	0.006439
58.15996	6
0.002411	0.000249

Sand 1406.10 g
Water 1234.47 g
Naphthol 0.2362 g
Sand and water pre-mixed for 10 minutes

Surface Area 2.52E-03 m2
Liquid Volume 1.24E-03 m3
Solid Volume 5.31E-04 m3
Total Volume 1.77E-03 m3

Ks = 1.22E-05 m/s

svf = 0.30
Slurry Holdup = 8.7



Solids Volume Fraction Varying Set of Data

RUN 12 April 11/94 Sand and Naphthol

R.P.M. 2.90 Size 425-500 micron

Cs 0.74 4 Baffles

Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)
1	0	0.104	0.0108	0.0000
2	5	0.175	0.0181	0.0101
3	10	0.168	0.0174	0.0091
4	15	0.403	0.0413	0.0427
5	25	0.500	0.0512	0.0570
6	35	0.621	0.0634	0.0749
7	45	0.684	0.0698	0.0844

Regression	
0.002041	0
0.000122	#N/A
0.945456	0.007938
104.0035	6
0.006554	0.000378

Sand 2302.68 g

Water 886.73 g

Naphthol 0.2104 g

Sand and water pre-mixed for 10 minutes

Surface Area 2.24E-03 m2

Liquid Volume 8.88E-04 m3

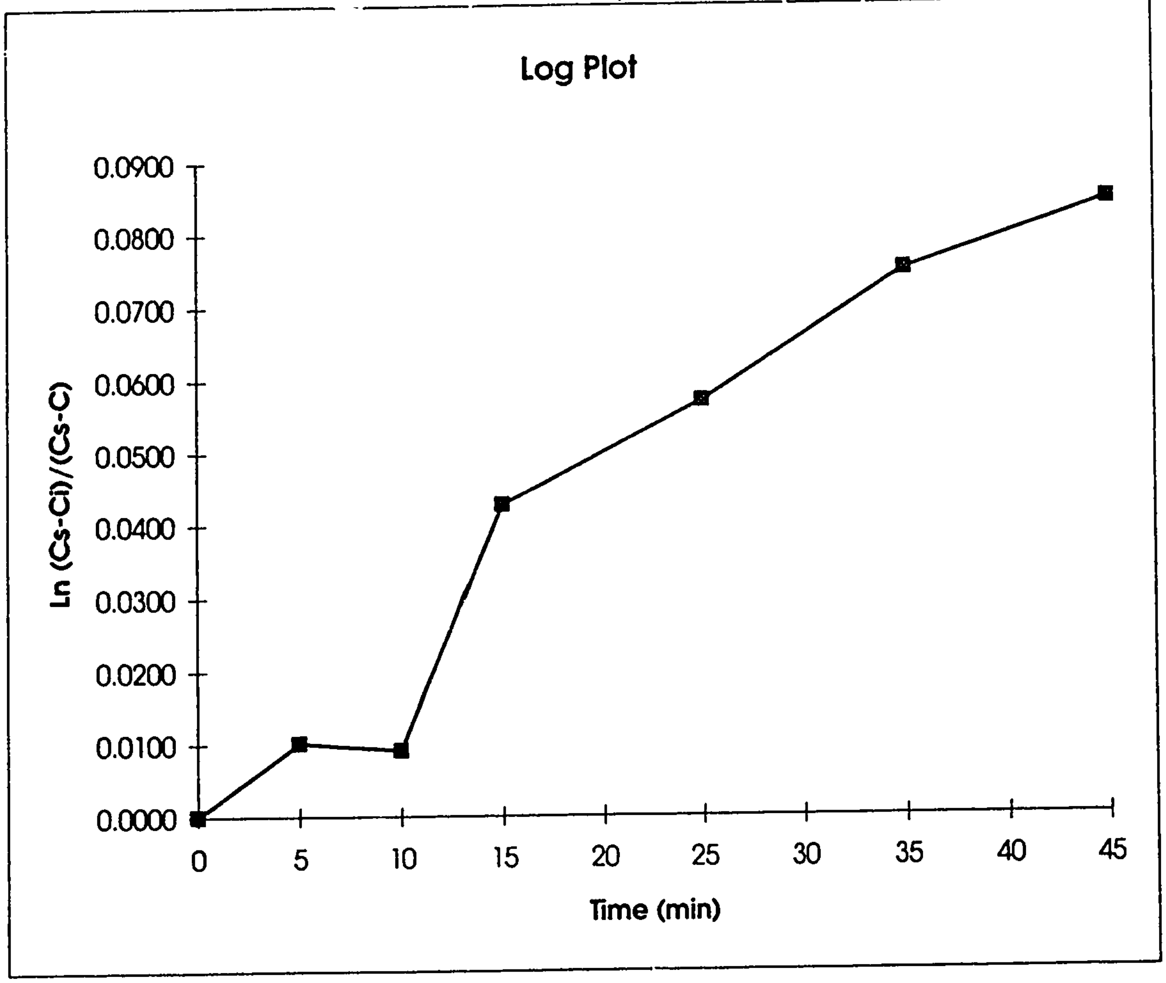
Solid Volume 8.69E-04 m3

Total Volume 1.76E-03 m3

Ks = 1.35E-05 m/s

svf = 0.49

Slurry Holdup = 8.5



Large Drum, Drum Rotational Speed Varying, Set of Data

RUN 1	June 3/94	Sand and	Naphthol			
R.P.M.	3.69	Size	425-500 microns			
Cs (g/l)	0.74	4 Baffles				
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)	Regression	
1	0	0.119	0.0124	0	0.004111	0
2	5	0.288	0.0296	0.0239	6.97E-05	#N/A
3	10	0.416	0.0425	0.0422	0.996344	0.001908
4	15	0.547	0.0559	0.0616	1090.231	4
5	20	0.675	0.0689	0.0808	0.00397	1.46E-05

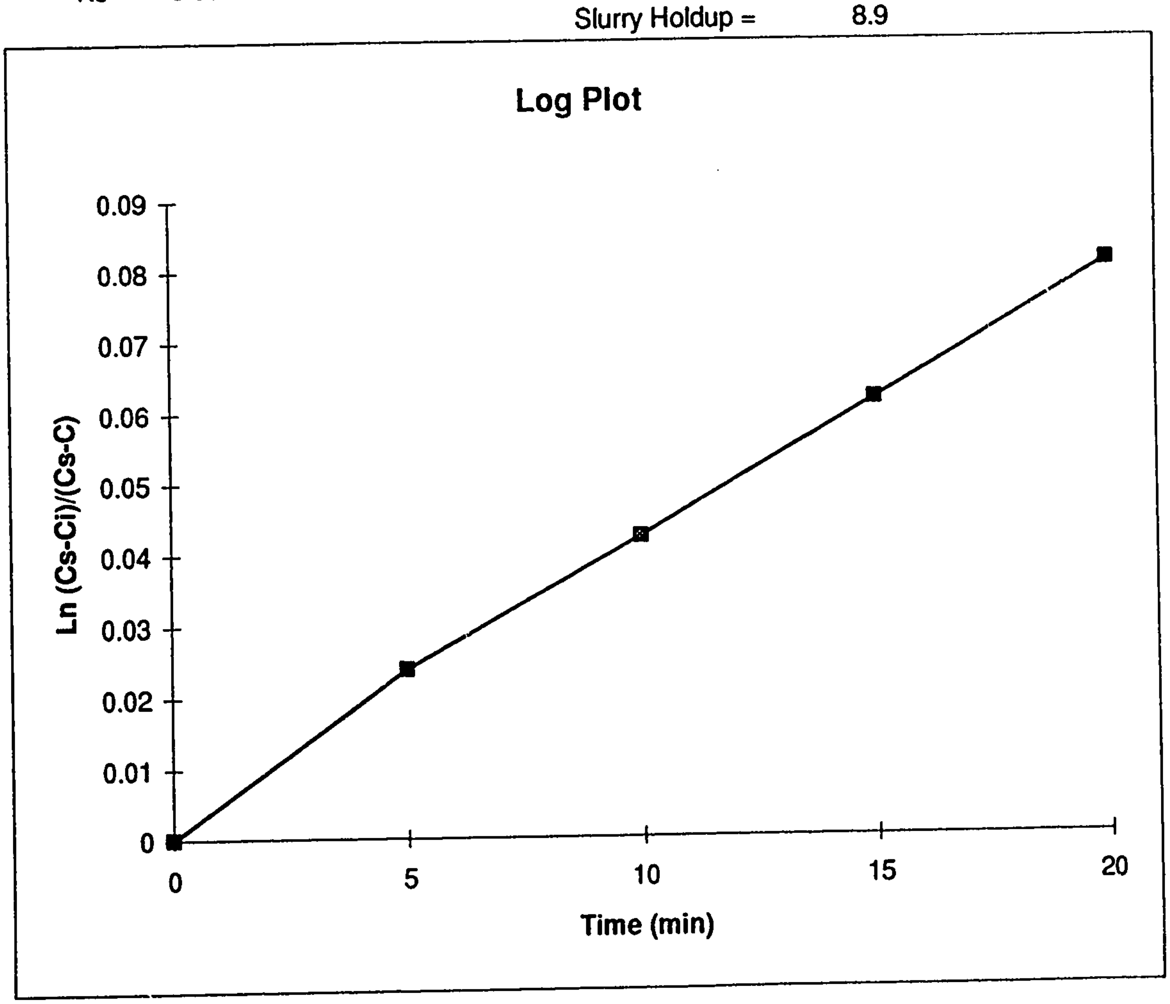
Sand	24044.08 g	Surface Area	2.33E-02 m2
Water	12007.94 g	Liquid Volume	1.20E-02 m3
Naphthol	2.19 g	Solid Volume	9.07E-03 m3
		Total Volume	2.11E-02 m3

Sand and water pre-mixed for 20 minutes

Ks = 3.53E-05 m/s

svf = 0.43

Slurry Holdup = 8.9



Large Drum, Slurry Holdup Varying, Set of Data

RUN 1	June 17/94	Sand and	Naphthol			
R.P.M.	0.73	Size	425-500 microns			
Cs (g/l)	0.74	4 Baffles				
Sample	Time (min)	Abs	Conc (g/l)	Ln (Cs-Ci)/(Cs-C)	Regression	
1	0	0.053	0.0057	0	0.005608	0
2	5	0.180	0.0186	0.0177	0.000553	#N/A
3	10	0.376	0.0385	0.0457	0.936895	0.010353
4	15	0.705	0.0719	0.0945	44.53986	3
5	20	0.706	0.0720	0.0946	0.004774	0.000322

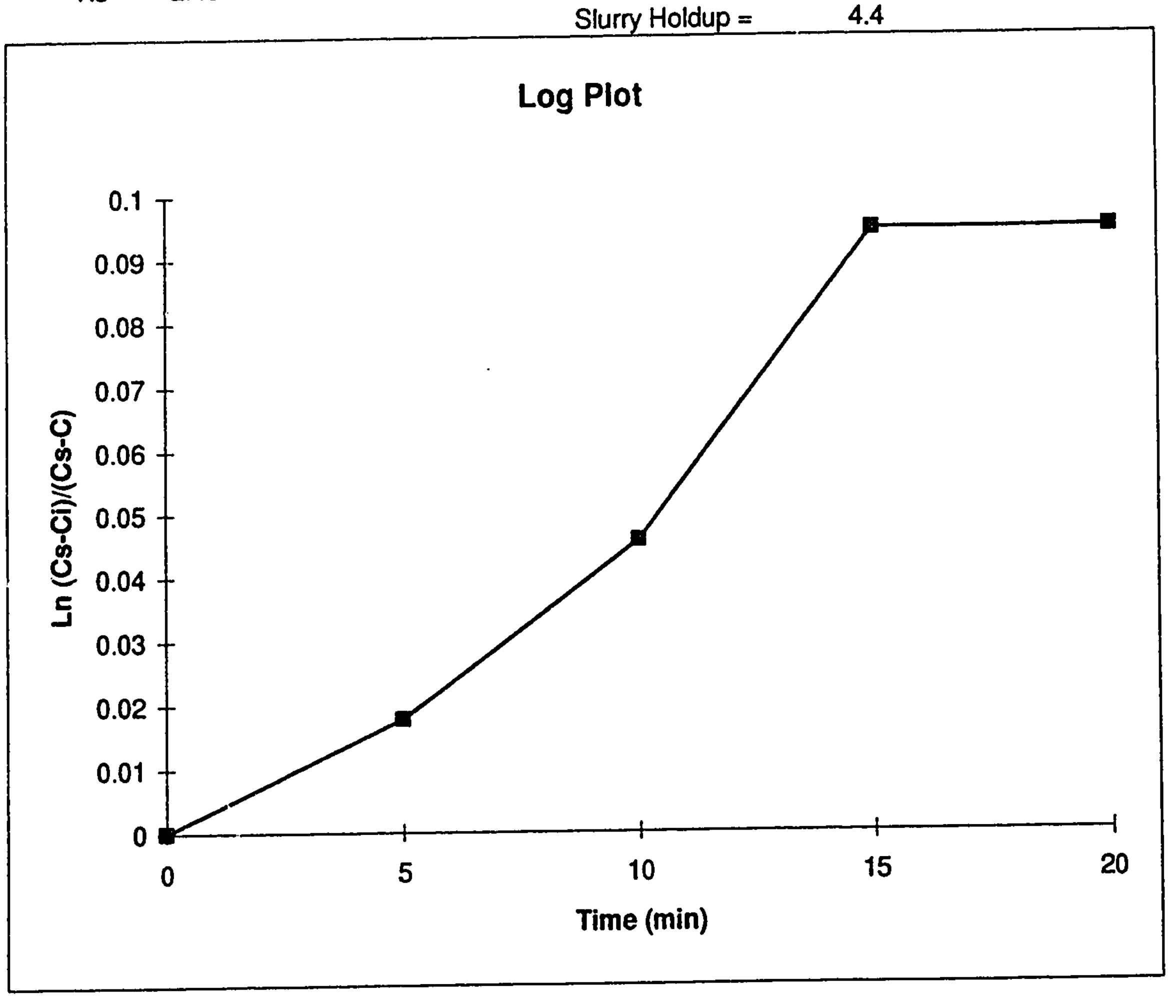
Only the first 15 minutes were analyzed

Sand	12018.74 g	Surface Area	2.26E-02 m2
Water	6004.79 g	Liquid Volume	6.02E-03 m3
Naphthol	2.12 g	Solid Volume	4.54E-03 m3
Sand and water pre-mixed for 10 minutes		Total Volume	1.06E-02 m3

Ks = 2.49E-05 m/s

svf = 0.43

Slurry Holdup = 4.4



Sample Calculation for the Second Order Solution for k_s.

For this example, the results from the 9th experiment conducted in the drum rotational speed varying set of data will be used (rotational speed of 15 rpm). The following equation (equation (4-19)) is calculated using the data obtained from the UV spectrophotometer (C_s is the solubility concentration of β-naphthol in water, which is 0.74 kg m^{-3}, C is the concentration of β-naphthol in water at time t, and C_i is the concentration of β-naphthol in water at time zero).

$$y_1 + y_2 + y_3 = a_1 \, a_2^{2/3} \, t \qquad \text{(A-1)}$$

where the y_is are defined as (previously defined in equation (4-20,21,22):

$$y_1 = \ln \left[\frac{C_s - C_i}{C_s - C} \right] \qquad \text{(A-2)}$$

$$y_2 = 2/3 \; a_4 \left(C_i - C - C_s \ln \left[\frac{C_s - C}{C_s - C_i} \right] \right) \qquad \text{(A-3)}$$

$$y_3 = -5/9 \; a_4^2 \left(C \, (C_s + 1/2 \; C) - C_i \, (C_s + 1/2 \; C_i) + C_s^2 \ln \left[\frac{C_s - C}{C_s - C_i} \right] \right) \qquad \text{(A-4)}$$

Each data point is calculated and then plotted as shown in Figure 4-5. The slope of the line is obtained through linear regression and used in the following equation (equation (4-23) to obtain k_s:

$$k_s = \frac{\text{slope } V (1 - \alpha)}{a_2^{2/3}} \tag{A-5}$$

where the a_is are defined as:

$$a_1 = \frac{k_s}{V (1 - \alpha)} \tag{A-6}$$

$$a_2 = A_i^{3/2} + \frac{6 \sqrt{\pi N_p} V (1 - \alpha) C_i}{\rho_p} \tag{A-7}$$

$$a_3 = \frac{6 \sqrt{\pi N_p} V (1 - \alpha)}{\rho_p} \tag{A-8}$$

$$a_4 = \frac{a_3}{a_2} \tag{A-9}$$

The slope for the example used above (run #9 in the rpm varying set of data) is 9.97 x 10^{-5}, V is the total slurry volume and is obtained from the data sheet ($V=1.76 \times 10^{-3}$ m^3), α is the solids volume fraction (svf) and is equal to 0.43 for this experiment. The above equation (equation (A-2)) is used to calculate a_2, where A_i, the initial surface area is:

$$A_i = 4 \pi r_{p i}^2 N_p \tag{A-10}$$

where r_{pi} is the initial radius of the β-naphthol particles (equal to 2.3×10^{-4} m). Equation (4-8) can be rearranged to obtain an expression for N_p:

$$N_p = \frac{m}{4/3\ \pi\ r_{p\,i}^3\ \rho_p} \qquad \text{(A-11)}$$

where m is the mass of β-naphthol particles put into the drum (for this case equal to 2.048×10^{-4} kg) and ρ_p is the density of the β-naphthol particles (1217 kg m^{-3}). For this case the mass transfer coefficient, k_s, is equal to 4.4×10^{-5} m s^{-1}.

Final Results

RUN	RPM	Slurry Holdup, %	Solids Volume Fraction	ks, m/s x E05	Height, h m	Froude # Fr3	Sherwood #
rpm1	2.90	8.6	0.43	1.70	0.035	0.020	18
rpm2	5.00	8.6	0.43	2.60	0.035	0.035	27
rpm3	5.00	8.6	0.43	2.20	0.035	0.035	23
rpm4	7.10	8.6	0.43	2.70	0.035	0.050	28
rpm5	9.00	8.6	0.43	3.10	0.036	0.063	32
rpm6	11.00	8.6	0.43	3.30	0.039	0.077	34
rpm7	13.00	8.6	0.43	4.00	0.040	0.091	41
rpm8	15.00	8.6	0.43	4.40	0.040	0.105	45
rpm9	15.00	8.6	0.43	4.40	0.040	0.105	45
rpm10	1.20	8.6	0.43	0.90	0.035	0.008	9
rpm11	0.38	8.6	0.43	0.60	0.036	0.003	6
rpm12	0.50	8.6	0.43	1.10	0.035	0.004	11
rpm13	2.10	8.6	0.43	1.00	0.035	0.015	10
rpm14	0.33	8.6	0.43	1.50	0.036	0.002	15
sh1	3.22	4.4	0.43	0.94	0.030	0.023	10
sh2	3.10	6.6	0.43	1.20	0.032	0.022	12
sh3	3.19	8.8	0.43	1.80	0.036	0.022	19
sh4	3.17	11.0	0.43	2.20	0.039	0.022	23
sh5	2.95	13.0	0.43	2.00	0.042	0.021	21
sh6	3.05	15.0	0.43	1.90	0.044	0.021	20
sh7	3.18	8.7	0.43	1.90	0.036	0.022	20
sh8	3.07	17.0	0.43	2.00	0.046	0.022	21
sh9	3.07	4.4	0.43	0.80	0.030	0.022	8
sh10	3.01	17.0	0.43	1.90	0.046	0.021	20
sh11	2.95	15.0	0.43	1.80	0.044	0.021	19
sh12	3.02	6.6	0.43	1.40	0.032	0.021	14
sh13	3.05	11.0	0.43	1.60	0.039	0.021	16
sh14	3.08	13.0	0.43	1.70	0.042	0.022	18
svf1	3.00	8.6	0.43	0.96	0.036	0.021	10
svf2	3.08	8.7	0.00	1.60	0.043	0.022	7
svf3	3.03	8.7	0.30	1.10	0.040	0.021	9
svf4	2.99	8.7	0.49	1.60	0.033	0.021	19
svf5	3.00	8.4	0.62	2.30	0.033	0.021	37
svf6	3.02	8.7	0.15	1.40	0.044	0.021	9
svf7	3.07	8.7	0.00	1.50	0.043	0.022	7
svf8	3.04	8.7	0.56	1.90	0.033	0.021	26
svf9	3.06	8.6	0.43	1.80	0.036	0.021	19
svf10	3.01	9.7	0.13	1.40	0.044	0.021	8
svf11	2.97	8.7	0.30	0.98	0.040	0.021	8
svf12	2.99	8.6	0.50	2.00	0.033	0.021	24
bdrpm1	3.69	8.9	0.43	3.90	0.084	0.038	40
bdsh1	0.73	4.4	0.43	2.80	0.052	0.007	29

APPENDIX B

Sample Calculation for Froude Number (Fr_3).

The following equation (equation (4-27)) is used to calculate Froude number:

$$Fr_3 = \frac{V_\omega}{\sqrt{g\ D\ (S_s\ -1)}} \tag{B-1}$$

where V_ω is defined as:

$$V_\omega = N\ R_d \tag{B-2}$$

where N is the rotational rate, s^{-1}, and is defined as:

$$N = \frac{(rpm)\ 2\ \pi}{60} \tag{B-3}$$

The density ratio, S_s, (ρ_s/ρ_w) for all sets of experiments is equal to 2.65. For this example the data from run #9 in the drum rotational speed varying set of experiments will be used. The small drum was used in this experiment, therefore, R_d will be 0.145 m, D will be 0.29 m and the rpm is 15. The Froude number will be 0.11.

Sample Calculation for Sherwood Number.

The equation used to calculate Sherwood number is equation (4-33) and is repeated here:

$$Sh = \frac{k_s D_p}{D_{mix}} \tag{B-4}$$

To calculate D_{mix} equation (4-32) is used:

$$\frac{D_{mix}}{D_{aqu}} = 1 - \alpha^{2/3} \tag{B-5}$$

where D_{aqu} is the diffusivity of β-naphthol in water (1.0443×10^{-9} m^2 s^{-1}). For this example the data from run #9 in the drum rotational speed varying set of experiments will be used. For this experiment, α is 0.43, D_p (particle diameter of the solids) is 4.63×10^{-4} m and k_s is 4.4×10^{-5} m s^{-1}. The Sherwood number, for this case, was calculated to be 45.

APPENDIX C

Sample Calculations for k_L'.

For the calculation of k_L', equations (2-6), (2-9), and (2-10) were used. For the present study the shape factors β_i and ψ_i are set equal to one, therefore, for this case equation (2-6) looks like this:

$$k_L\ a = \frac{\alpha}{1-\alpha}\frac{6}{D_p}k_s \qquad \text{(D-1)}$$

Equations (2-9) and (2-10) do not change and are repeated here:

$$(k_L\ a)' = k_L\ a\ \frac{1-\alpha}{\alpha} \qquad \text{(D-2)}$$

$$k_L' = D_p\ (k_L\ a) \qquad \text{(D-3)}$$

For this example run #9 of the drum rotational speed varying set of data was used, where k_s is 4.4 x 10^{-5} m s^{-1}, α is 0.43, and D_p is 4.63 x 10^{-4} m and k_L' is calculated to be 2.64 x 10^{-4} m s^{-1}.

APPENDIX D

Constants

C_s = solubility of β-naphthol = 0.74 kg m^{-3}

r = radius of particles = 2.3125 × 10^{-4} m

D_p = diameter of particles = 4.625 × 10^{-4} m

D_{aqu} = diffusivity of β-naphthol = 1.0443 × 10^{-9} m^2 s^{-1}

in water@20 °C

ρ_p = density of β-naphthol = 1217 kg m^{-3}

ρ_s = density of sand = 2650 kg m^{-3}

ρ_w = density of water@20 °C = 998.04 kg m^{-3}

μ_w = viscosity of water@20 °C = 1.02602 × 10^{-3} kg m^{-1} s^{-1}

D_d = diameter of drum = 0.29 m

L = length of drum = 0.308 m

D_{ld} = diameter of large drum = 0.58 m

L_{ld}= length of large drum = 0.90 m