EFFECT OF FLUIDIZATION ON MASS TRANSFER BEHAVIOR IN THE ELECTRODEPOSITION ON PARALLEL PLATE ELECTRODE

BY

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CERTIFICATION OF THESIS WORK

We, the undersigned, certify that SHIMUL KANTI ROY, candidate for the degree of Master of Science in Engineering (Chemical) has presented his thesis on the subject "EFFECT OF FLUIDIZATION ON MASS TRANSFER BEHAVIOR IN THE ELECTRODEPOSITION ON PARALLEL PLATE ELECTRODE". The thesis is acceptable in form and content. The student demonstrated a satisfactory knowledge of the field covered by this thesis in an oral examination held on January 15, 1998.

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ABSTRACT

The present work has been undertaken to study mass transfer rate in a vertical parallel plate cell using copper electrode and acidified (sulfuric acid) copper sulphate solution. It has been aimed to study the nature of deposition during copper electroforming.

The mass transfer rates under different hydrodynamic conditions within the cell were obtained measuring the current at different sections of the cathode. Mass transfer data were generated using limiting current technique. Flow rate was varied in the range of 5.8 lit/min to 16.3 lit/min and initial bed height was taken to be 6 cm, 9 cm 12 cm and 15 cm. Glass beads of three different diameters 1 mm, 2 mm, and 3 mm were used to investigate the effect of particle size on mass transfer rate.

Results were obtained for wide range of flow rates of the electrolyte and overall mass transfer correlations were obtained for the cell. The flow rate, initial bed height and bed voidage for maximum mass transfer were found out. The results were correlated and compared with the relevant correlation found in the literature.

An extensive literature survey of the basic principles governing the theory behind different electrochemical processes and electrochemical mass transfer has been done in this study.

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CHAPTER - 1

1. INTRODUCTION

Eletrodeposition of metal from solution during processe like electrowinning, electrorefining, electroplating and electroforming are industrially important. Electroplating is performed by deposition of metal films on machinery, Engineering components and other articles for protecting them against corrosion and imparting a pleasing appearance to them or indowing them with specific properties such as hardness, wear resistance, antifrictional properties, electrical and magnetic properties. Electrowinning is the primary recovery of metals by electrodeposition from solutions containing metal ions and is capable of producing high purity deposits from dilute and moderately concentrated solution. Electrorefyning means purifying a metal by a combination of dissolution of metal from impure anode and deposition of pure metal at the cathode. Electroforming involves controlled deposition to a conducting mandrel of predetermined shape, size, accuracy and surface finish through production of articles by electrolysis. Subsequently the mandrel is intentionally removed to leave an electroform.

The above cathodic processes should be operated at high current densities. But this might sometimes produce poor and uneven deposit because the rate of mass transfer is not uniform through out the electrode. In electrochemical reactors, where one of the reactions is fast, the study of mass transfer is very important. Mass transfer study is especially very important to the chemical engineers because it determines the maximum mass transfer rate at which the reactor can be efficiently operated. The maximum practical operating current depends mainly on the hydrodynamic conditions prevalent at the electrodes. Electrodeposition of metal from solutions are generally fast reactions and are important industrially in processes mentioned above.

Mass transfer studies of electrochemical processes are done in order to ensure good quality deposits, because if the rate of mass transfer is not uniform and intensive over the whole of electrode then poor or uneven deposition may occur. Generally operation at low current densities gives good quality deposits but the rate of mass transfer is not uniform over the whole of the electrode and locally high rates can cause poor electrodeposition. Well defined and controlled forced convection can give rise to better and uniform rates of deposition.

In order to improve the performance of an electrolytic cell, one can either raise the limiting current density or increase the specific electrode area. Agitation is the most important means by which the former may be significantly increased. The effect of increased solution concentration may be of comparable magnitude but flexibility may be limited by considerations of solubility and deposit quality. In the past decade there has been considerable effort in the research and development of fluidized bed electrochemical reactors, although inert fluidized beds, in which nonconducting solid particles are fluidized have received limited attention. Quantitative analysis of mass transfer behavior and the optimum conditions for operation have not been studied thoroughly.

In the present research work, a parallel plate cell has been used due to ease of design, construction and maintenance and for the uniformity of current distribution. The chosen shape of the cell also provides a surface area to volume ratio second only to particulate cells. In this study Cu-$CuSO_4$ system has been used. Since the cathodic reaction for the chosen system is mass transfer controlled, the use of sectioned cathodes enables the current distribution and flow development to be studied by the limiting current technique.

Experimental mass transfer data have mainly been obtained in systems with long hydrodynamic entrance and exit regions thus ensuring that the flow is fully developed When applied to the design of practical reactors such data results in over design. Moreover, entrance regions of the above kind are not desirable in the working reactors. Keeping the above facts in view, the present work has been undertaken to investigate the mass transfer rate in the cathodic deposition of copper from acidified solutions of copper sulphate using a fluidized bed cell with sudden expansion at the inlet and contraction at the outlet. Different sizes of spherical glass beads have been used to study the effect of particle size on mass transfer. The cell has been operated under different flow conditions and initial bed heights to study the effect of flow rate and bed voidage on the mass transfer. Although in the present system, dilute solutions have been preferred to keep the limiting currents small and to cause slow dissolution of the anode, the experimental results gathered can be adequately used for industrial processes.

Experimental results are presented and correlated for different cell conditions. Comparisons have been made between the present study and the previous relevant works.

CHAPTER-2

2. LITERATURE REVIEW

2.1 INTRODUCTION

In this chapter main features of fluidized beds, mass transfer in fluidized bed reactors and mass transfer theories in parallel plate electrochemical reactors have been studied. Work done by the previous researchers in the relevant areas have also been included.

2.2 MASS TRANSFER THEORIES IN ELECTROCHEMICAL CELLS

2.2.1 Mass Transfer In Parallel Plate Systems For Fully Developed Laminar Flow

At steady state and in presence of excess in different electrolyte, the flux equation may be written as

$$U_x \frac{\delta C_i}{\delta x} + U_y \frac{\delta C_i}{\delta y} + U_z \frac{\delta C_i}{\delta z} = D_i \left(\frac{\delta^2 C_i}{\delta x^2} + \frac{\delta^2 C_i}{\delta y^2} + \frac{\delta^2 C_i}{\delta z^2} \right) \tag{2.1}$$

where,

U = velocity

D_i = diffusion coefficient of species i

C_i = concentration of species i.

For parallel plate reactors, considering flow in the x direction, equation (2.1) reduces to

$$U_x \frac{\delta C}{\delta x} = D_i \frac{\delta^2 C}{\delta y^2} \tag{2.2}$$

Leveque [22] obtained an approximate solution of equation (2.2) for analogous heat and mass transfer cases. His solution was

$$Sh = \frac{Kd_e}{D} = 1.85\left(Re\ Sc\ \frac{d_e}{L} \right)^{1/3} \tag{2.3}$$

Where,

Sh = Sherwood number

Re = Reynolds number

Sc = Schmidt number

K = average mass transfer coefficient

de = equivalent diameter of the cell

L = electrode length.

Pickett and Stanmore [27] derived an approximate relationship for mass transfer coefficient in a rectangular duct of finite dimensions, using parabolic velocity distributions in the y direction only, of the form

$$Sh = 1.467\left(Re\ Sc\ \frac{de}{L} \right)^{\frac{1}{3}} \left(\frac{2}{1} + \gamma \right)^{\frac{1}{3}} \tag{2.4}$$

where,

γ = aspect ratio, b/a

a = width of the electrode

b = distance between the electrodes

Tobias and Hickman [44] experimentally verified the Leveque solution. They obtained

$$Sh = 1.85\left(Re\ Sc\ \frac{de}{L} \right)^{\frac{1}{3}} \tag{2.5}$$

$$Sh = 2.54 \; Re^{\frac{1}{3}} \; Sc^{0.292} \left(\frac{de}{L}\right) \tag{2.6}$$

In 1982, Ali [1] has correlated his experimental data for a rectangular duct, as

$$Sh = 1.21 \; Re^{0.49} \; Sc^{\frac{1}{3}} \left(\frac{de}{L}\right)^{0.22} \tag{2.7}$$

which compares very favorably with the Walker and Wragg [48] prediction.

2.2.2 Mass Transfer In Turbulent Flow

The most useful empirical expression available for mass transfer in turbulent flow is the Chilton and Colburn analogy. Chilton and Colburn [9] presented an empirical heat transfer relationship as

$$J_h = St_h \, (Pr)^{\frac{2}{3}} = 0.023 \; Re^{-0.2} \tag{2.8}$$

where,

St_h = Stanton number for heat transfer

Pr = Prandtl number

J_h = Colburn J factor for heat transfer

The right hand side of equation (2.8) is equal to half the friction factor (f) defined as $f = 0.046 \; Re^{-0.2}$, and this leads to a general relationship for mass transfer as

$$St(Sc)^{\frac{2}{3}} = \frac{f}{2} = 0.023 \; Re^{-0.2} \tag{2.9.a}$$

or,

$$Sh = 0.023 \; Re^{0.8} Sc^{\frac{1}{3}} \tag{2.9.b}$$

where St is the mass transfer Stanton number.

The equation (2.9) is the best known empirical correlation for predicting mass transfer in turbulent flow and has been applied successfully to various flow systems.

Hubbard and Lightfoot [16] found form their experimental studies that mass transfer in turbulent conditions is best represented by the Chilton and Colburn analogy in the ranges of $10^4 < Re < 5 \times 10^4$ and $1 < Sc < 1000$.

$$Sh = 0.063 \; Re^{0.92} Sc^{\frac{1}{3}} \tag{2.10}$$

All the correlations mentioned are for fully developed velocity and concentration profiles and are limited in application because they can not be used for reactors in which the flow is not fully developed.

2.2.3 Simultaneously Developing Flow And Mass Transfer

Bird et al. [3] developed an equation for flow in a duct which is suitable for situations when the flow has not fully developed but is laminar. They derived the equation for mass transfer problem with relevant boundary conditions as :

$$Sh = \frac{K de}{D} = \frac{2}{\sqrt{\pi}} \left(Re \; Sc \; \frac{de}{L} \right)^{\frac{1}{2}} \tag{2.11}$$

Using electrochemical methods to measure mass transfer coefficient entrance region for developing mass transfer boundary layer. Berger and Hau [5] correlated their experimental data by

$$Sh = 0.0165 \; Re^{0.86} Sc^{0.35} \tag{2.12}$$

Pickett and Stanmore [27] obtained an empirical equation

$$Sh = 0.145 \ Re^{0.6} Sc^{\frac{1}{3}} \left(\frac{de}{L} \right)^{\frac{1}{4}} \qquad (2.13)$$

which is appropriate for parallel plate with L/de < 7.5.

2.2.4 Effect Of Flow Entrance Shape On Flow Developments And Mass Transfer

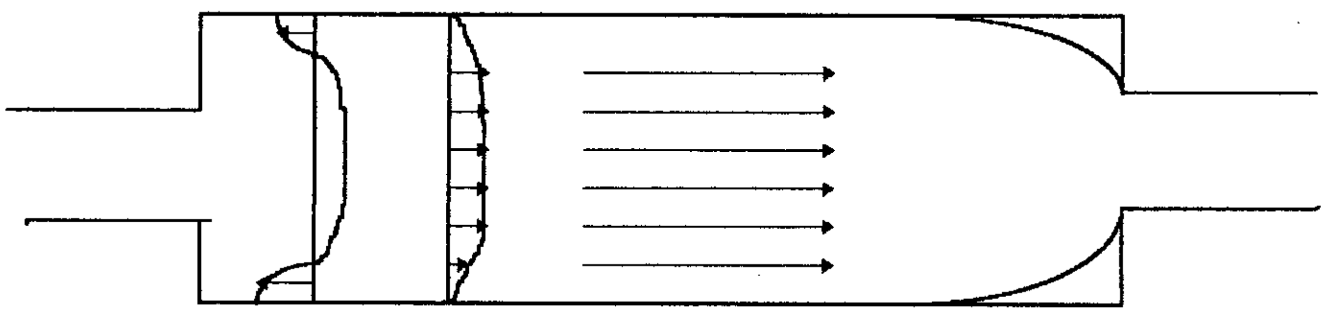


Fig. 2.1: Velocity profile changes due to sudden expansion and contraction.

After sudden expansion, a secondary flow occurs in the boundary layer due to a superimposed external flow field and its direction deviates from that of the external flow. The particles, near the flow axis have a higher velocity and are acted upon by a larger centrifugal force than the slower particles near the wall and this leads to secondary flow directed outwards in the centre and inwards near the wall. Regions of boundary layer separation and backflow are formed due to secondary flows and the backflow in the boundary layer leads to the formation of eddies. These eddies occur in regions where there is an adverse pressure difference.

Krall and Sparrow [20] investigated the heat transfer in the separated, reattached and redeveloped regions in a circular pipe by passing flow through orifices varying from 1/4 to 2/3 of the pipe diameter. They found that the position of the maximum heat transfer coefficient is independent of Reynold's number, although its value is directly proportional to the Reynold's number. They also found that the position of maximum heat transfer occur at position of 1.25 to 2.25 diameter downstream from the point of entry. In recent times, Runchal [36], Wilson [50], and Wragg, Tagg and Patrick [52] have studied axial local mass transfer distributions immediately downstream of sudden changes in flow cross sectional area using the limiting current technique. Their results were in good agreement with those of Krall and Sparrow [20]. They found the value of mass transfer co-efficient for fully developed turbulent flow to be in agreement with the Dittus Boelter equation.

Their correlation is :

$$Sh = 0.023\ Re^{0.88} Sc^{0.4} \tag{2.14}$$

2.3 MAIN FEATURES OF FLUIDIZATION SYSTEM

2.3.1 Conditions for Fluidization

When a fluid is passed through a bed of solid particles, initially the particles do not move. But as the velocity is gradually increased the pressure drop across the bed counter balances the force of gravity on the particles or the weight of the bed. With a further increase in fluid velocity the particles become separated enough to move about in the bed and fluidization begins.

2.3.2 Particulate And Aggregate Liquid Fluidization

If liquid velocity through a bed of solid particles is gradually increased, a point is reached when effective weight of each particle is just supported by the drag on it. If there is nothing restraining the top surface, the bed at this point transforms itself from a fixed to a fluidised bed. The velocity at incipient fluidisation is called the minimum fluidisation velocity U_{mf}.

If the flow rate of the liquid is increased above the minimum fluidisation velocity to produce a fluidised bed, one of the two things will occur; either the bed will continue to expand so that the average distance between the particles will increase uniformly, or the excess fluid will pass through the bed in the form of bubbles. These two types of fluidization are referred to as particulate fluidisation and aggregate fluidisation respectively.

2.3.3 Pressure Drop Velocity Relationship

For a fluid passing vertically upwards through a bed of solid particles, the pressure drop, ΔP, will initially rise as the velocity, U, is increased as shown by the AB region in Fig. 2.2. The relation between pressure drop and velocity will be the same as that of a fixed bed. When the superficial velocity has reached such a value that the frictional pressure drop is equal to the effective weight per unit area of the particles, any further increase in velocity must result in a slight upward movement of the bed. The particles will become rearranged so that the resistance to fluid flow is decreased. In general the voidage of the bed will increase and in an idealised system, the pressure drop will remain constant as shown by the CD region of Fig. 2.2.

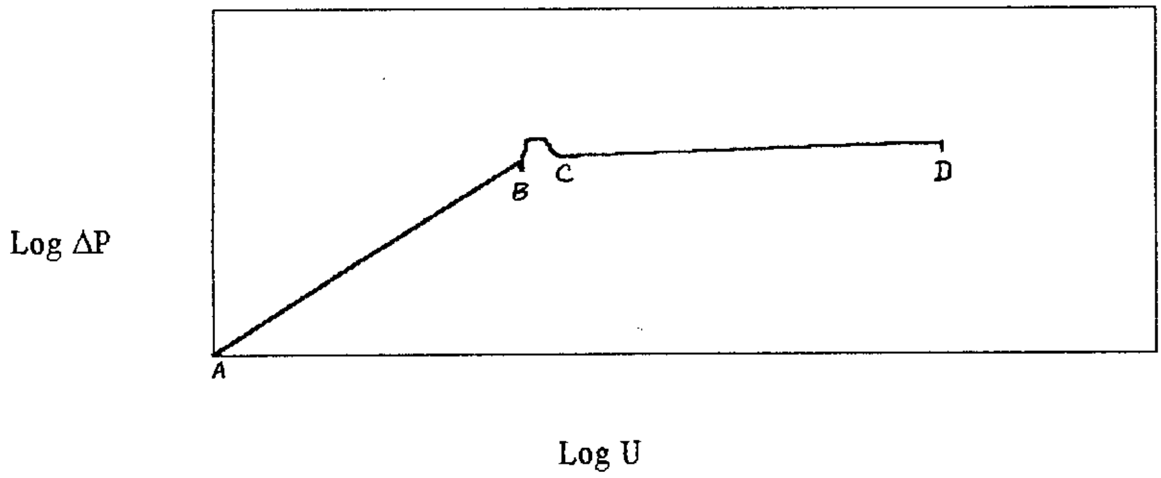


Fig. 2.2 : Pressure drop-velocity curve.

At this stage the bed is just fluidised; it is said to be the point of incipient fluidisation and the superficial velocity at this point is known as the minimum fluidising velocity, U_{mf}. As the fluid velocity is further increased, the pressure drop over the bed remains constant.

2.3.4 Characteristics of Bed Expansion

According to a number of workers, most convenient way of showing the variation of fluidizing velocity with voidage is on a logarithmic plot since it gives a linear relationship. This can be expressed as

$$U / U_i = \varepsilon^n \qquad (2.15)$$

where U is the fluidisation velocity and U_i is the fluidization velocity at the voidage (ε) of unity.

The exponent, n, is a function of the ratio of particle diameter to bed diameter (d_p/D_e) and Reynolds number Re_t (= $U_t\, d_p\, \rho_f/\mu$), involving the free-falling velocity of the particles and the size of the particles. The following empirical correlations for uniform spherical particles were obtained experimentally for U_i and n by Richardson and Zaki [34].

For fluidisation relation between U_i and terminal settling velocity is :

$$\log U_i = \log U_t - \frac{d_p}{De} \qquad (2.16)$$

$$n = 4.65 + 20\frac{d_p}{D_e} \qquad (Re_t < 0.2) \qquad (2.17)$$

$$n = 4.4 + 18\frac{d_p}{D_e} Re_t^{-0.03} \qquad (0.2 < Re_t < 1) \qquad (2.18)$$

$$n = 4.4 + 18\frac{d_p}{D_e} Re_t^{-0.1} \qquad (1 < Re_t < 200) \qquad (2.19)$$

$$n = 4.4 + Re_t^{-0.1} \qquad (200 < Re_t < 500) \qquad (2.20)$$

$$n = 2.4 \qquad (Re_t > 500) \qquad (2.21)$$

Of all correlations, despite its limitations, Richardson and Zaki correlation remains most widely used.

2.3.5 Bubble Formations In Fluidized Beds

It is very important to know the type of fluidization in any practical application of liquid fluidized beds. The mass transfer, heat transfer and mixing properties of the bed may undergo a dramatic change with a particulate aggregate transition. A fluidized bed is called bubbling when there exists fluid regions devoid of particles. Bubbles form due to the hydrodynamics of the fluid-particle interaction. With an even sintered plate distributor, bubbles form very close to the distributor as particles free small voids.

The formal classification of fluidized systems as particulate or aggregate is due to the early work of Wilhelm and Kwauk [49] based on the concept of inter-particle forces in the vicinity of the bubbles. They suggested a dimensionless group, the Froude number at minimum fluidization, $U^2_{mf}/g\ d_p$, as a criterion. From their experimental results they suggested, for $Fr_{mf} >> 1$, aggregate behavior will be observed. For $Fr_{mf} << 1$, particulate behavior will dominate and for Fr_{mf} of the order of 1, the system is transitional.

2.4 MASS TRANSFER IN A FLUIDIZED BED ELECTRODE

2.4.1 Mass Transfer Correlation For Fluidized Bed

Fluidization represents an essentially unstable situation between packed bed operation and hydraulic transport. This implies that relations describing transfer coefficients for the above operations will show much similarity. The segregation of the phases in a fluidized bed leads to a transfer resistance specific for this operation. Experimental studies of mass transfer at a flat plate or cylindrical surface show that mass transfer rate increases with increase in the electrolyte velocity. In fluidized condition, the inert glass beads give additional kinetic energy to disrupt the concentration boundary layer and enhance mass transfer at the wall.

The usual way of correlating mass transfer data is by means of a dimensionless group correlation of the following form :

$$St = \text{constant} \times Sc^{c}\, Re^{b} \tag{2.22}$$

where the Stanton No. St (= K/U) is a mass transport coefficient, the Schmidt No. Sc (= ν/D) describes the transport characteristics of the fluid and the Reynolds number Re (= Ud_p/ν) describes the pattern of fluid flow. Much of the early work on fluidised beds was correlated by means of the particle diameter d_p, but more recently the mean hydraulic diameter of the voids has been considered to be more appropriate in the case of inert particles. This has been shown in Fig 2.3 in which the bed is represented as a series of N hydraulic channels and (N+1) columns of particles. For simplicity it is assumed that all channels are of equal width. It is also assumed that the velocity in this channel is proportional to the interstitial velocity, U, in the bed and that the hydraulic diameter of this channel is proportions to the mean hydraulic diameter of the voids between the particles. For the two dimensional section, the area of particles present can be expressed as:

$$(N + 1)\, L_f\, d_p = A(1 - \varepsilon) \tag{2.23}$$

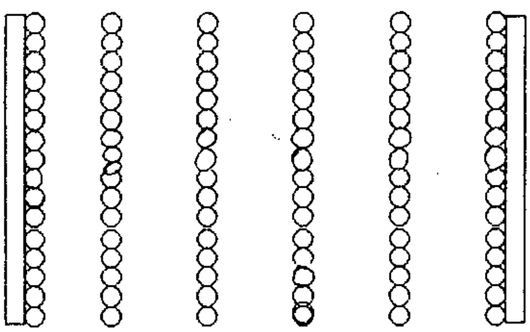


Fig. 2.3: Model for fluidized bed.

where A is the total area of section and ε is the bed voidage. The area of hydraulic voids is then given by :

and

$$N \; L_f \; d_h = A\varepsilon \qquad (2.24)$$

where d_h is the hydraulic diameter. Elimination L_f from equation (2.23) and (2.24)

$$d_p = \left(\frac{N}{N+1}\right)\left(\frac{1-\varepsilon}{\varepsilon}\right) d_h \qquad (2.25)$$

Equation (2.25) can be further simplified by assuming that (N/N+1) → 1 where N is very large.

$$d_p = \left(\frac{1-\varepsilon}{\varepsilon}\right) d_h \qquad (2.26)$$

Hence a modified Reynolds number can be defined using the hydraulic diameter;

$$Re_1 = \frac{U_o d_p \varepsilon}{\upsilon(1-\varepsilon)} \qquad (2.27)$$

where U_o is the actual velocity of fluid within the voids. This is related to the superficial velocity U by :

$$U_o \, \varepsilon = U \qquad (2.28)$$

They by substitution;

$$Re_1 = \frac{U d_p}{\upsilon(1-\varepsilon)} \qquad (2.29)$$

Defining Stanton Number in terms of superficial velocity as :

$$St_1 = \frac{K\,\varepsilon}{U} \qquad (2.30)$$

Hence the modified dimensionless correlation becomes :

$$St_l = \text{Constant}\ (Sc)^c\ (Re_l)^b \tag{2.31}$$

The mean hydraulic diameter may also be defined in terms of the effective cross sectional area of flow i.e., the volume of voids and the surface area of the solid particles, A_p as :

$$d_h = \frac{k_c\ V_v}{A_p} \tag{2.32}$$

where k_c is a constant. But as the volume of voids is given by $V_v = V_b\varepsilon$, where V_b is the total volume of the bed. The surface/ volume ratio of the solid spherical particles is $6/d_p$, it may be written as :

$$d_h = \frac{k_c\ d_p}{6} \cdot \left(\frac{\varepsilon}{1 - \varepsilon}\right) \tag{2.33}$$

If the value of k_c is 6, equation (2.26) and (2.33) become identical.

2.5 REVIEW OF PREVIOUS WORKS ON MASS TRANSFER IN FLUIDIZED BEDS

Krishna et al. [21] used a system for the oxidation of ferrocyanide ion and the reduction of ferricyanide ion. They used equimolar solution of potassium ferrocyanide and potassium ferricyanide (0.01M) with excess of different electrolyte (0.5N sodium hydroxide) as the fluidizing medium. They used rockwood shot and glass spheres of different sizes (1 mm to 5 mm) with annular electrodes. They obtained a correlation:

$$J_D\varepsilon = 0.43\ (Re_l)^{-0.43} \tag{2.34}$$

Rama Rao and Venkata Rao [32] used a square channel packed bed instead of annular channel and they suggested the correlation as :

$$J_D\varepsilon = 0.79\ (Re_l)^{-0.404} \tag{2.35}$$

Carbin and Gabe [7] studied the mass transfer behavior using cylindrical test electrode in a cylindrical bed. They used ballotini glass beads (0.1 mm ~ 0.3 mm) such that $D_e/d_p \geq 80:1$. They found the maximum value of limiting current density at a voidage $\varepsilon = 0.59$. With their experimental results, they suggested the correlation to be

$$St_l \,(Sc)^{\frac{2}{3}} = 1.24 \; Re_l^{-0.57} \tag{2.36}$$

Smith and King [39] studied the ionic mass transfer coefficients between the wall of a tube (2") and liquid fluidized beds of lead glass, soda glass and lucite spheres using diffusion controlled reduction of ferricyanide ion at a nickel cathode for porosities 0.90 to 0.45 and Schmidt numbers 580 to 2100. The developed fluidization mass transfer coefficient for $41 < D_e/d_p < 105$ were:

$$J_D \varepsilon = 0.274 \; Re_l^{-0.38} \qquad \text{for } 10 < Re_l < 1600 \tag{2.37}$$

and by $J_D \varepsilon = 0.455 \; Re_l^{-0.44}$ for $16.7 < D_e/d_e < 27$. (2.38)

$$50 < Re_l < 3500$$

The distinct effect of D_e/d_p ratio is attributed to the wall effects and non particulate behavior of the fluidized bed for large size particles.

Coeuret and Goff [11] reviewed the problem of mass transfer in an immersed cylindrical surface and the liquid in a fluidized bed of nonconducting spherical particles. Their electrolyte solution consisted of equimolar solution (0.005 M) of Potassium ferrocianide and ferricyanide with excess of indifferent electrolyte (0.5 NaOH). Their data exhibited a maximum mass transfer coefficient (K) at a voidage of 0.55 < e < 0.6. They found the correlation to be :

$$J_D = 1.20 \; Re_l^{-0.52} \tag{2.39}$$

Walker and Wragg [48] performed electrochemical experiments involving the cathodic deposition of copper from aqueous solutions containing H_2SO_4 in a rectangular channel.

They determined mass transfer rates at a plane wall electrode in the presence of a fluidized bed of glass beads. They found the correlation as :

$$J_D \varepsilon = 0.138 \ Re_l^{-0.39} \quad for\ 0.936 < Re_l < 67 \tag{2.40}$$

They also found maximum mass transfer rate to occur at a voidage of 0.7 ~ 0.75.

TABLE 2.1

Comparison of mass transfer correlations according to:

$$St_I \cdot Sc^{\frac{2}{3}} = a \, Re_I^b$$

Author(s)	a	b	D_e/d_p	System	Re_I	Sc	Particle size (mm)
Smith and King	0.32 0.54	0.38 0.44	41-105 17-27	Cylindrical wall mass transfer	0.7-1067 34-2334	580-2100	- -
Jattrand and Grunchare	0.45	0.375	93-36	Planar test electrode in cylindrical bed	6-200	1250	0.220-0.780
Jagannadharaju and Venkata Rao	0.43	0.38	8-27	Inner anode of annular bed	200-3800	1300	1.54-6.00
Coeuret et al.	1.20	0.52	93-290	Various cylindrical probes	6-200	1250	0.35-1.07
Carbin and et al.	1.24	0.57	80-150	Cylindrical test electrode in cylindrical bed	0.1-70	787-1777	0.185-0.355
Walker and Wragg	0.138	0.39	43	Rectangular channel wall mass transfer	0.936-67	2675	0.274-0.548
Gomes E.	0.049 0.038 0.019	0.40 0.30 0.25	9.5 6.3 4.8	Rectangular channel wall mass transfer	675-3238 1473-5300 2015-5934	1150-1710 1300-1760 1100-1760	3.0 4.5 6.0

Zaman Khan Piroz, Malinen P. and Lepomaki H. [52] pointed out that (in the boundary layer of coarse particles) momentum transport due to collisions between particles and between particles and Cu^{++} ions plays the most important role in the particle motion and in the transport of Cu^{++} ions. Theyworked on a vertical rectangular cell. The relative velocities between particles and Cu^{++} will lead to collision between them. The change in velocity of a fine particle after a collision increases probability of collisions between Cu^{++} ions. Since the Cu^{++} ions affect the velocity of each other, the increase in velocity of a Cu^{++} ions and ultimately the velocity of all the Cu^{++} ions increases.

Takehara K. and Takerhara H. [43] worked on electrochemical cell for electroplating and obtained same type of V-I curve. They also observed the presence of a monolayer of the anode and obtained the following empirical correlation.

$$Cr(0,t) = Cr^{*} - (nFACr^{*}Dr^{1/2})^{-1}\int_{o}^{t}\frac{i(u)}{(t-u)^{1/2}}du \qquad (2.41)$$

where,

Cr^{*} = Bulk concentration of the electrolyte

Dr = Diffusion coefficient

n = Number of electron involved

A = Electrode area

i(u) = Electron current at time u.

They calculated the result with a numerical integration technique and multiplying the result by $Cr^{*}/Cr(0, t)$ to eliminate diffusion limitation.

Tsao, J.L. and Liang S.F. [45] used rectangular duct with particles of diameter 1 mm and 2.1 mm. They presented their result on a liquid velocity vs. bed voidage diagram and mass transfer coefficient vs. velocity diagram. They obtained same velocity for maximum mass transfer coefficient and maximum voidage was about 0.8.

In an earlier report Sedahmed et al. [37] studied the effect of liquid velocity on mass transfer. The mass transfer data was correlated by the equation,

$$J = 0.187\,(\mathrm{Re}\,Fr)^{-0.26} \tag{2.42}$$

According to Cavatora and Bohm

$$Sh = a_1 (Sc\,Ga)^{0.33}\,\Sigma^{n} \tag{2.43}$$

where a_1 and n are functions of geometry of transfer surface and range of experimental conditions.

Kolmogroffs correlated his result as $St\,Sc^{0.5} = a_2(\mathrm{Re}\,Fr)^{-0.25}$ (2.44)

where,

a_2 = 0.1 for heat transfer

a_2 = 0.035 for mass transfer

St = Stanton number

Sc = Schemidt number

Re = Reynolds number

Fr = Froude number

Zaki, M.M., Nirdosh I. and Sedahmed, G.H. [53] correlated their results as $St\,Sc^{0.5} = 0.095\,(\mathrm{Re}\,Fr)^{0.2.72}$

They plotted their typical polarization curve and fluid velocity vs. mass transfer curve. This curve shows similarity with that of present study.

Rao, K.R., [31] obtained

$Sh = K_L\,ad^2/D$

$Sc = (\mu/\rho D)$

K_L = mass transfer coefficient (m/s)

d = unit length parameter (m)

a = interfacial area of contact between phases, (m^2/m^3)

D = liquid diffusivity, (m^2/sec)

μ = liquid viscosity, (Kg/s.m)

ρ = liquid density, (Kg/m^3)

CHAPTER - 3

3. EQUIPMENT AND EXPERIMENTAL PROCEDURE

3.1 INTRODUCTION

The passes of solution of salts of such metals as zinc, iron, nickel, cadmium, lead copper, silver and mercury results in the liberation of these metals at the cathode from the solution. A number of experiments were performed with a vertical parallel plate cell having copper electrodes in fluidized conditions. Different size of glass beads were used for fluidization. 0.015 M copper sulphate in 1.5 M sOulphuric acid as the electrolyte. According to previous workers the cathodic reaction is mass transfer controlled, and has direct bearing on existing electrochemical processes. The cathode was divided into several sections to allow current measurements of various sections and this enabled to determine the mass transfer rates at different positions in the cell. Glass beads of 1 mm, 2 mm and 3 mm were used to examine the effect of size and voidage on mass transfer. The average diameter of 50 beads of each size was used as the diameter of the related size.

3.2 MAIN EXPERIMENTAL SYSTEM

3.2.1 The Electrolytic Cell

The cell was constructed with perspex sheet of 1.2 cm thickness. It consisted of a inlet section, the anode side, the cathode side, the side plates and a exit section. The inlet and exit sections were provided to connect the cell to ½" PVC tubing. All the five parts were detachable. The electrolyte entered at the bottom and flowed upwards. There was no entrance length so that the mass transfer boundary layer and hydrodynamic boundary layer started at the leading edge of the electrode. Figures 3.1, 3.2 and 3.3 shows the five main units of the cell with detailed dimensions. Figure 3.4 is a sketch of the assembled cell with relevant dimensions as seen from the cathode side.

The dimensions of the cell (Figure 3.4) is 38.3 cm × 26.4 cm × 5.5 cm. Both the anode and cathode sides had the dimensions of 38.3 cm × 26.4 × 1.2 cm (Figure 3.2 and 3.3). The anode and cathode sides were kept at a distance of 2 cm from one another by side plates (38.3 cm × 2 cm and 1.2 cm thickness). Thus the total effective cross-sectional flow area of the cell was 20 cm × 2 cm (= 40 cm^2). The anode (Figure 3.2) was a piece of 3.2 mm thick copper plate (30.8 cm × 20 cm) glued with araldite into a groove of the same size and depth of 3.2 mm made into the perspex wall. The electrical connections were made with two 1.6 mm diameter copper wires soldered to the back of the anode through two 3.2 mm holes drilled at two positions.

The cathode (Figure 3.3) was 30.8 cm long and 20 cm wide and made of 3.2 mm thick copper plate. It was divided into fifteen sections from the leading edge of the electrode, the lengths of the sections were 1.0 cm for the first five (inlet) sections, 4.0 cm for the next five sections and 1.0 cm for the last five (exit) sections. The cathode sections were arranged in this manner as it was anticipated that the current and hence the mass transfer rates would vary significantly at the inlet and exit regions of the cathode. Smaller sections in these portions enabled more accurate measurements of the variations in current distribution. Each cathode section was fixed with Araldite to a groove of corresponding size cut into the perspex sheet and separated from the adjacent piece by thin strip of perspex of 0.2 cm thickness. This facilitated the measurement of the current in each section without interference from the neighbouring sections. Electrical connections to each cathode sections were made with fifteen 1.6 mm diameter copper wires soldered to the back of each cathode section through fifteen 3.2 mm holes in the cathode side perspex plate.

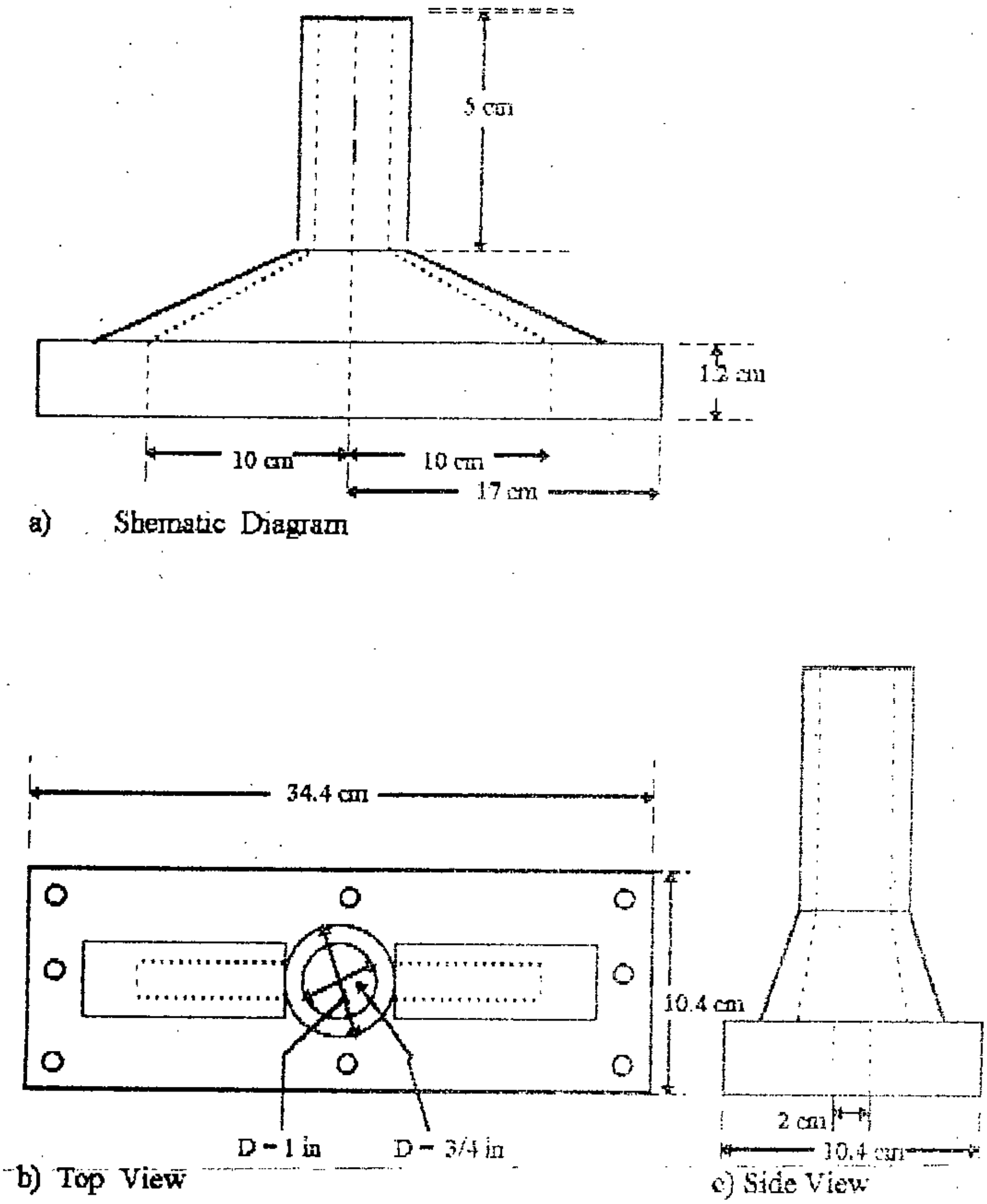


Figure: 3.1 - The Inlet and Exit Section

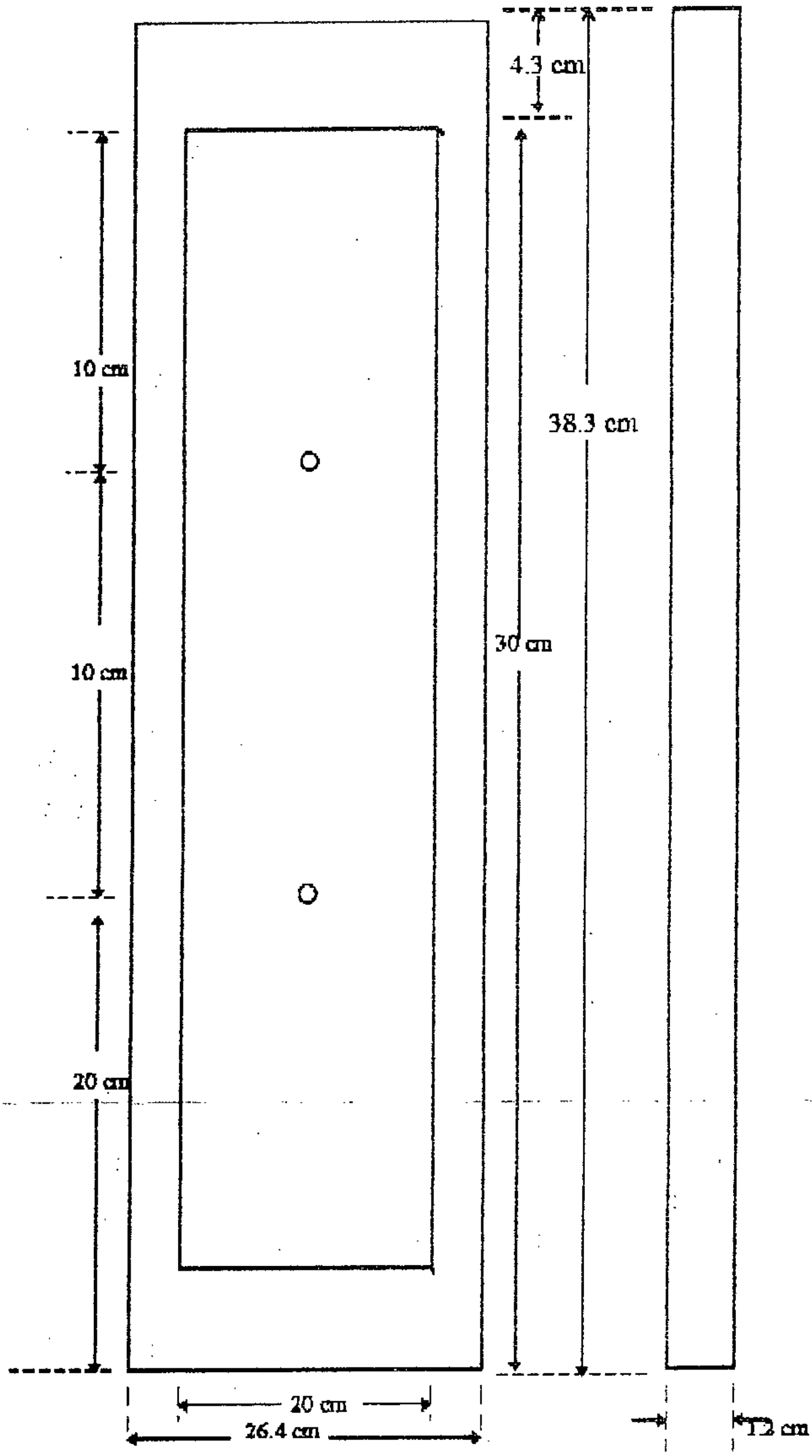


Figure: 3.2- The Anode Plate

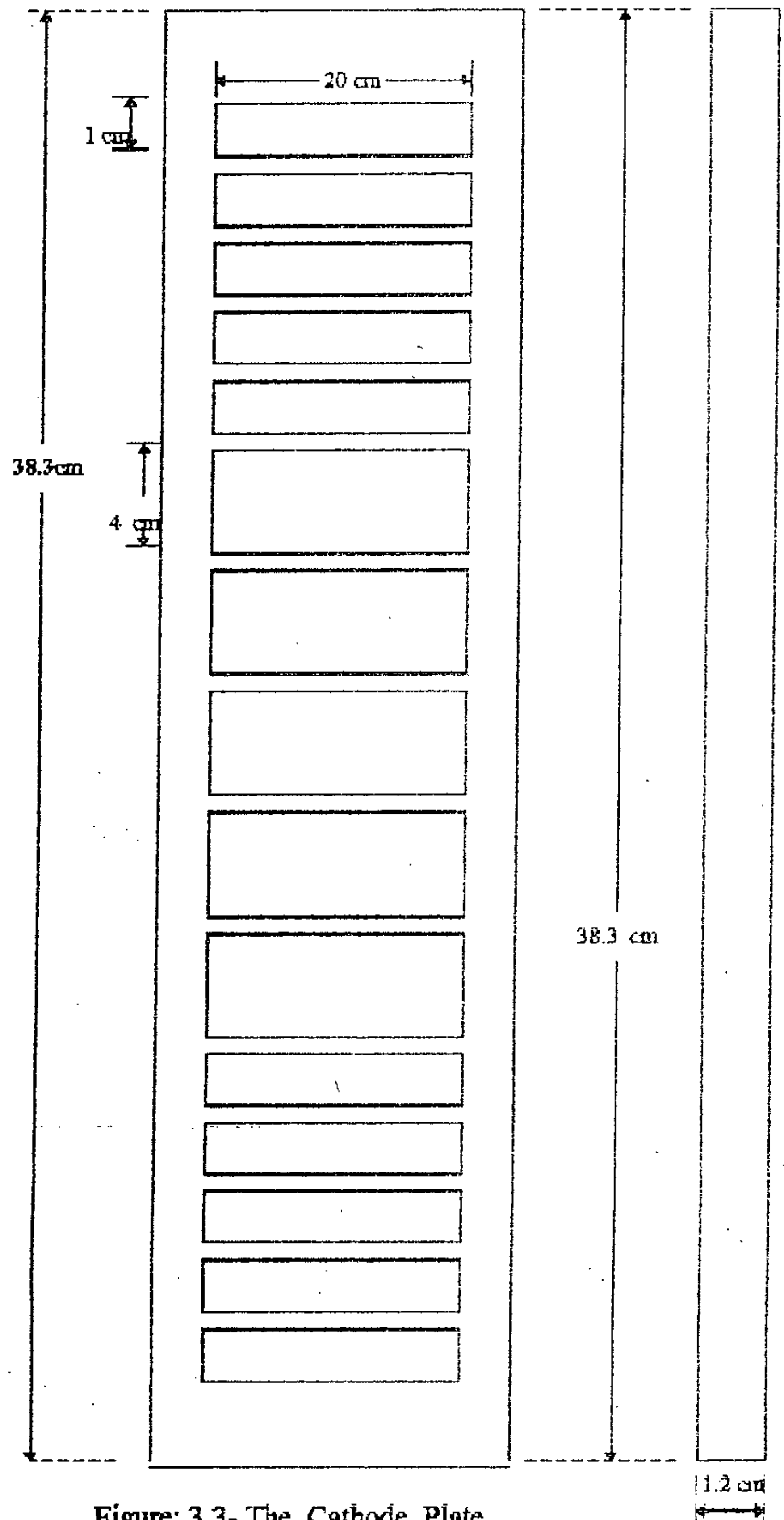


Figure: 3.3- The Cathode Plate

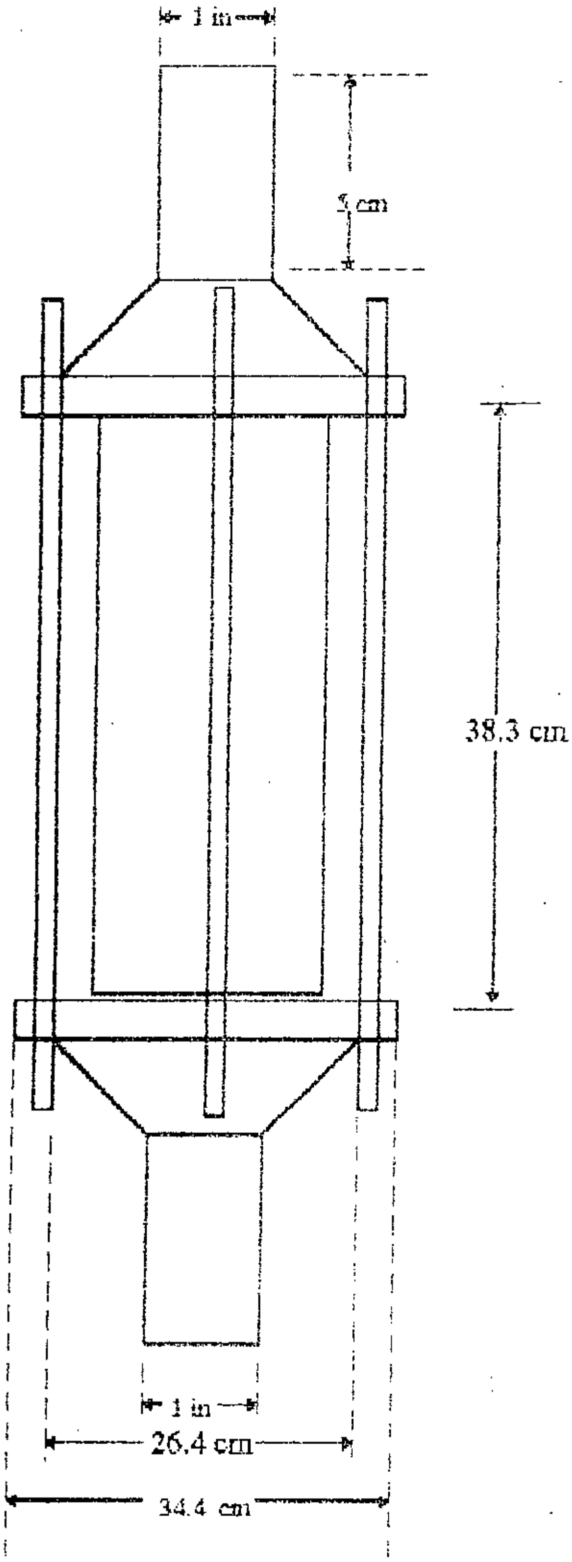


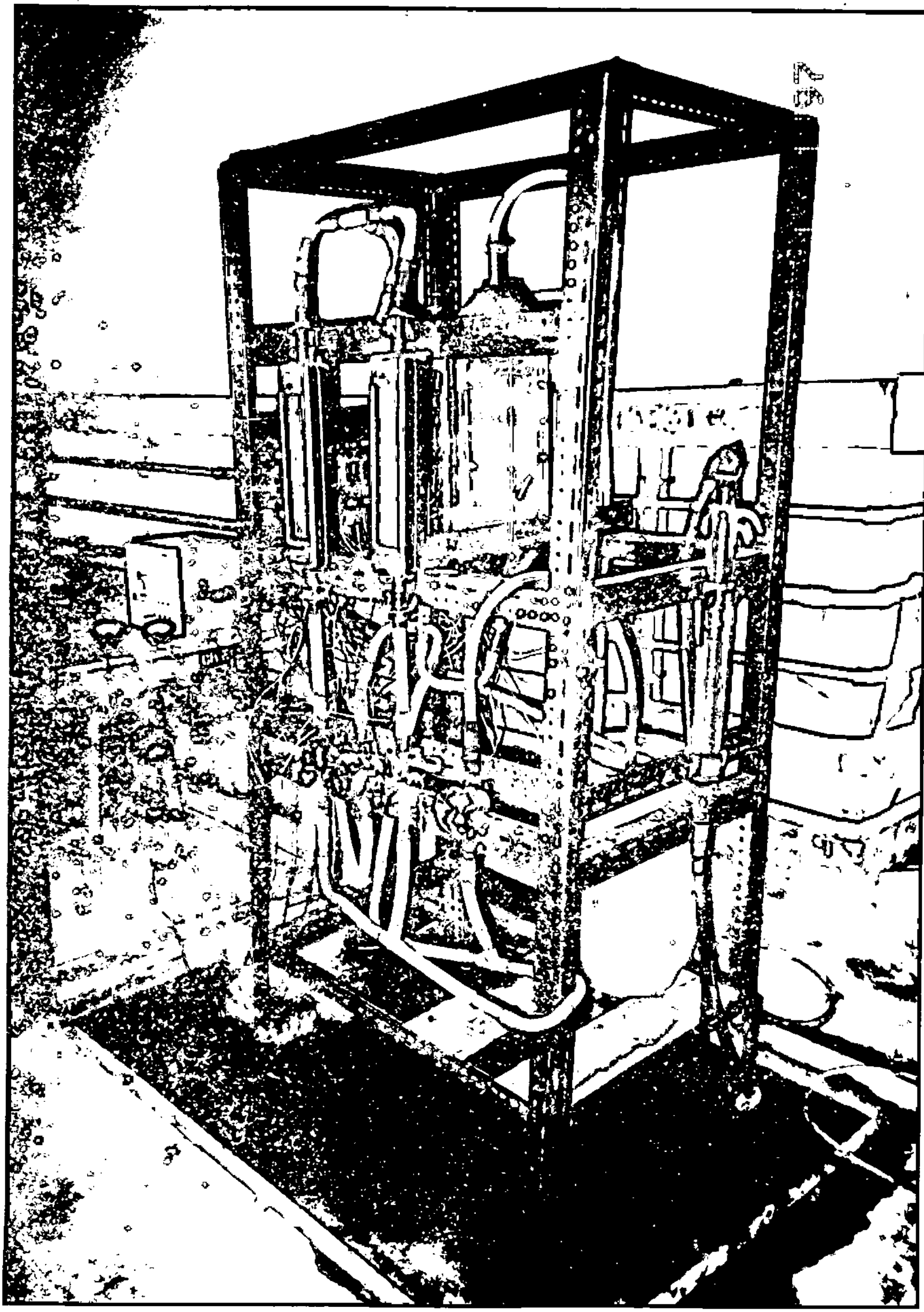
Figure: 3.4- The Overall Cell

The anode plate and side plates were joined together with the help of ethylene dichloride solvent. The anode and the cathode plates were joined together with nut and bolt at the top, middle and bottom regions. Two rubber gaskets were used between cathode plate and side walls to minimise the leakage. The main cell body and the inlet and outlet sections were joined together with 6.4 mm diameter brass tie rods through 6.4 mm holes in the inlet and exit section flanges Rubber gaskets were used between the main cell body and inlet, exit sections to prevent leakage. Finally a thin layer of Araldite was applied to all the side to make the cell completely leak proof.

The inlet and outlet portions (Figure 3.1) of the cell were of identical shape and dimensions. The diameter of the inlet and exit piping adjacent to the main cell body was 1.2 cm and this diameter was flared to 1.5 cm the connection point to the ¾" PVC tubing for easy pressure fit. The size of the inlet and exit section plates were such that (34.4 cm × 10.4 cm × 1.2 cm) they served as flanges to provide adequate space for the tie rods. Two steel wire meshes were used to support the bed particles and prevent them from escaping in the flow pipings and pump.

3.2.2 The Flow System

The whole flow system consisted of a pump, two rotameters, the electrochemical cell a cooler, a storage tank four two way glass valves and PVC pipes, tubes and fittings. Except the pump, all the major units were mounted on the experimental rig as shown in Figures 3.5. Figure 3.6 gives a detailed schematic diagram of the entire flow circuit. An Electronidioren Werke - Kaiser pump (220 V, 2.15 A, 0.25 KW and 50 Hz) with corrosion resistant plastic impeller and casing was used to circulate the acidified copper sulphate solution from a 25 Kg capacity plastic tank through the whole system. The flow line consisted of ¾" PVC pipes and tubes and the flow rate was measured by two rotameters of different ranges. The



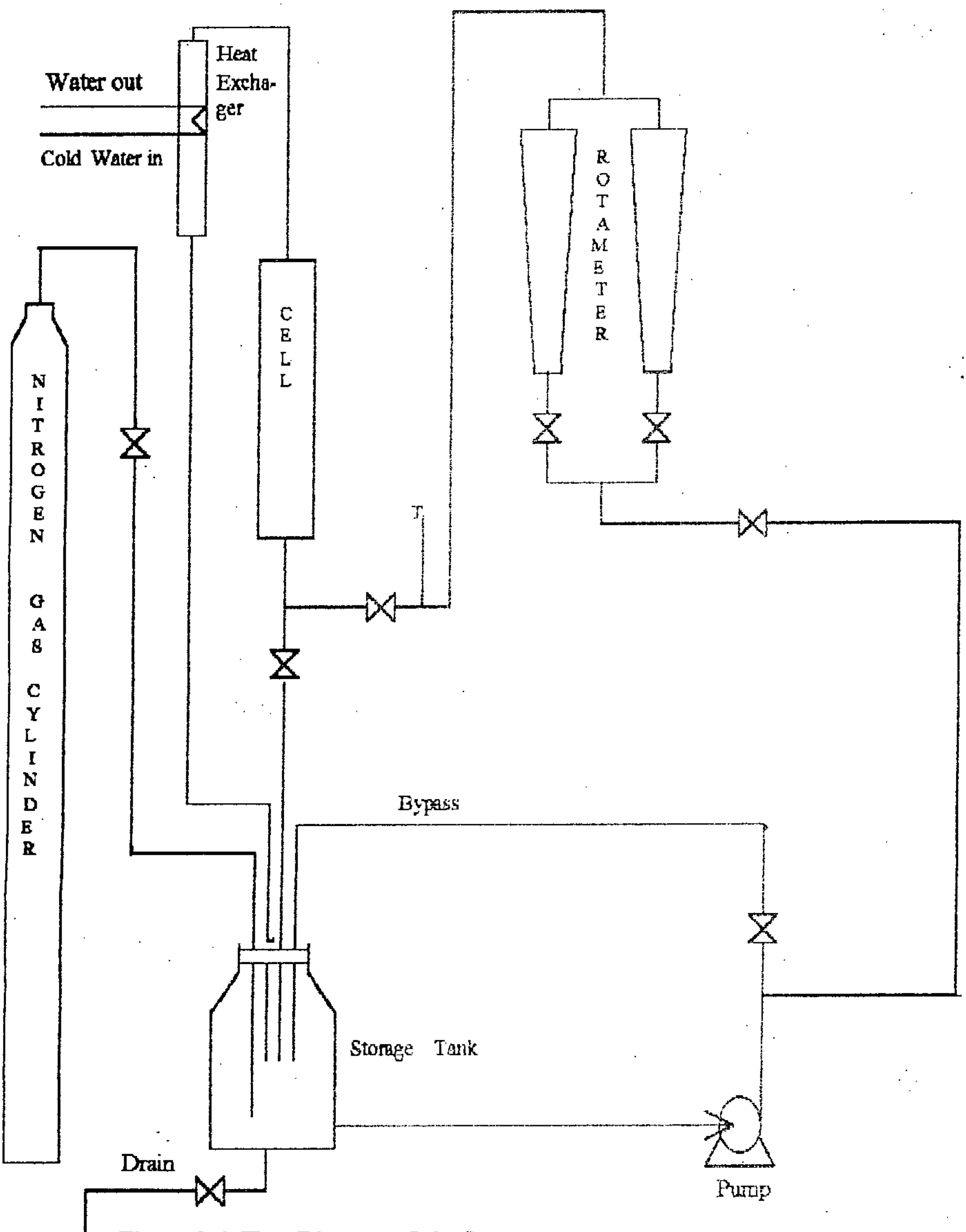


Figure: 3.6- Flow Diagram of the System

calibration curve for each rotameter for 0.015 M copper sulphate in 1.5 M sulphuric acid are presented in Appendix B. The flow through the cell was adjusted by using the flow bypass and the two way Pyrex ½" glass valves fitted before each rotameter. The flow direction in the cell was always vertically upwards. A cooler was used to prevent the increase of the electrolyte temperature although the temperature increased by several degrees after sufficient period of time. Two two-way control valves were used to control the flow direction as necessary. Dry nitrogen gas was used to deoxygenate the solution before each experiment.

3.2.3 The Electrical Circuit

An electrical circuit was designed for the electrochemical reactor which would allow the measurement of current on each section of the cathode separately without interfering the main electrolytic process or changing the total current passing through the cell. The electrical circuit is shown in Figure 3.7.

A d.c. power supply (PHYWE, 0-20V, 12A) connected with 220 V line was used as the power source. The total cell voltage was measured by a voltmeter placed across the cell. The total current passing through the cell was measured by a d.c. ammeter (Weston Instruments Company, 0-0.6A). The individual sectional currents were measured with a digital multimeter.

Toggle switches of current rating 10A were used to switch away any section of the cathode from the main circuit, through the ammeter A2 the cathode current of that section was measured. In this way the cathode current in all the sections were measured in turn.

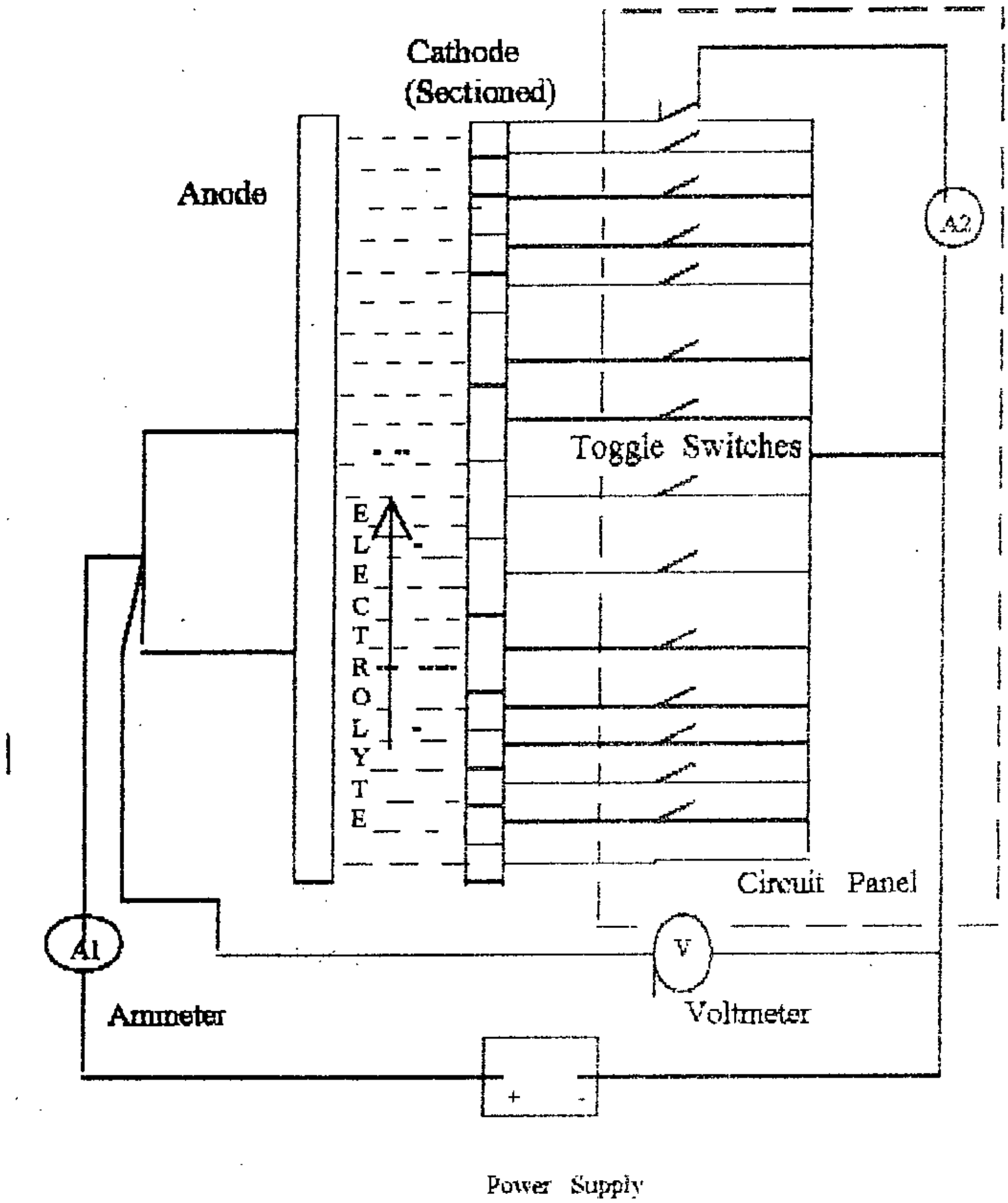


Figure: 3.7 - **Electrical** Circuit Used for Measuring Current
at Different Section of The Cell

3.2.4 Experimental Procedure

The concentration of copper sulphate solutions used in the experiments were approximately 0.015 M in 1.5 M sulphuric acid. Analytical grade anhydrous copper sulphate ($CuSO_4$) was dissolved in distilled water and sulphuric acid to make the electrolyte solution (0.015 M $CuSO_4$ in 1.5 M H_2SO_4 solution). The solution concentrations were determined volumetrically. The method used for the computation of the concentrations of copper sulphate is outlined by Jabbar et al. and Vogel involving precipitation of the copper as cuprous iodide with excess potassium iodide and titration of iodine formed with standard sodium thiosulphate solution. Analysis of the copper sulphate content was done after a series of runs. Dilute solutions of copper sulphate were used to ensure small limiting currents with correspondingly low rates of dissolution of the anode and deposition on the cathode and for minimum natural convection. Since the activation overpotential of an electrode is greatly dependent on electrode surface, both the electrodes were thoroughly cleaned before assembling the cell prior to each run. The cleaning was done by rubbing the electrode surface with successively finer grades of 'emery' paper. The electrodes were then rinsed with distilled water and degreased with an organic solvent (acetone). The smoothened electrode surface was finally washed with distilled water and left in air to dry.

The electrical connections to each cathode sections and the anode were cleaned and their electrical connections were checked by a multimeter before assembling the cell. The main body of the cell (i.e. anode plate, cathode plate and the sidewalls) was assembled first by three clamps. Then holding the main body on the inlet section, glass particles of a particular size (1.0 mm, 2.0 mm and 3.0 mm) were put into the cell upto a certain bed height. It may be mentioned here that for each particle size, four initial bed heights, such as 6.0 cm, 9.0 cm and 12.0 cm and 15.0 cm were used to make different voidages in the cell at different flow conditions.

At the start of each run nitrogen was passed through the solution in the storage tank from a gas cylinder for about 1-2 hours in order to deoxygenate the solution because an extra current density of approximately 0.25 mA/cm^2 is needed due to the reduction of oxygen at the cathode.

After deoxygenating the electrolyte, the pump was started and the electrolyte was recirculated through the system with flow rate adjusted by means of valves and the flow rate was measured from the rotameter. Before taking the readings, the cell was operated at low current densities (about 0.2 mA/cm^2) for about 15-20 minutes to get an even deposit of copper at the cathode. This was done by applying a small voltage across the cell from the power supply.

To investigate the limiting current at a given flow rate the applied voltage was set to a definite value with the help of the power source. Two to three minutes were allowed for the system to reach steady state before the current readings were taken. The bed height at fluidized condition was measured to find the voidage of the cell. The sectional current on the cathodes and the total cell currents were measured by two digital ammeters. The applied voltage was then increased in steps with intervals of 50 mV and the measurements were repeated until the individual currents in the sections exceeded their limiting values. This shows the start of the secondary reaction (i.e. hydrogen evolution at the cathode) and a sharp rise in current occurs. Between each run, the cell was dismantled, cleaned and reassembled. The experiment was repeated for different flowrates and different bed heights with different particle sizes.

The concentration of the solution was checked after taking readings for each size of particles, and negligible difference was found with the original value. In any case, the solution was replaced after taking readings for each particle size.

The problem with the cell was the continued cleaning of the electrodes required, since, repeated runs without cleaning did not reproduce the original results which is due to oxide formation on the anode surface. At the end of each run the anode was seen to be coated with a thin layer of black powder (copper oxide) which was formed by the reaction

$$Cu + 2H_2O \rightarrow Cu(OH)_2 + 2H_2$$

Moreover, difficulty was encountered due to the deposition of copper on the unexposed sides of the cathode as a result of leakage of electrolyte between cathode section and perspex plate. Again, at higher current densities, there was deposition of copper sulphate on the anode surface.

CHAPTER- 4

4. RESULTS AND DISCUSSION

4.1 INTRODUCTION

Studies on the enhancement of mass transfer on the deposition of copper from copper sulphate - sulfuric acid solutions were done using different type of glass beads as the fluidized particle and different types of hydrodynamic conditions. The cathode was divided into fifteen sections to measure the variation of current along the length of the cathode. Since only the cathodic deposition of copper is mass transfer controlled, mass transfer rate at different flow rates was measured. Fluidized bed electrolyte system was used to enhance the Cu^{+} ion deposition on the cathode. In the present work the concentration of the electrolyte was 0.015 M copper sulphate in 1.5 M sulphuric acid.

Currents along the length of the cathode were measured at different applied voltages until it exceed limiting current. The flow rate was increased from 5.8 liters/min to 16.3 liters/min the later being the maximum flow rate attainable by the pump. The size of the particle used was between 1.0 mm dia to 3.0 mm dia. Reynolds number range was from 108 to 762 for particle of 1 mm, 216 to 1525 for particle of 2 mm dia and 324 to 2286 for particle of 3 mm dia. The electrolyte was kept at about a constant temperature of 30^{0} C. The distribution of current and mass transfer coefficient at different section was determined. From this, the variation of mass transfer coefficient with distance from the leading edge of the electrode was calculated and the overall mass transfer coefficient was obtained for different flow rates. The variation of Sherwood number with Reynolds number and the correlation for the cumulative average mass transfer coefficient with distance from leading edge was obtained for different particles. The overall mass transfer correlation was obtained using different parameters such as flow rates, distance from the leading edge of the electrode (L/De) and aspect ratio.

4.2 REPRESENTATION AND ANALYSIS OF RESULTS

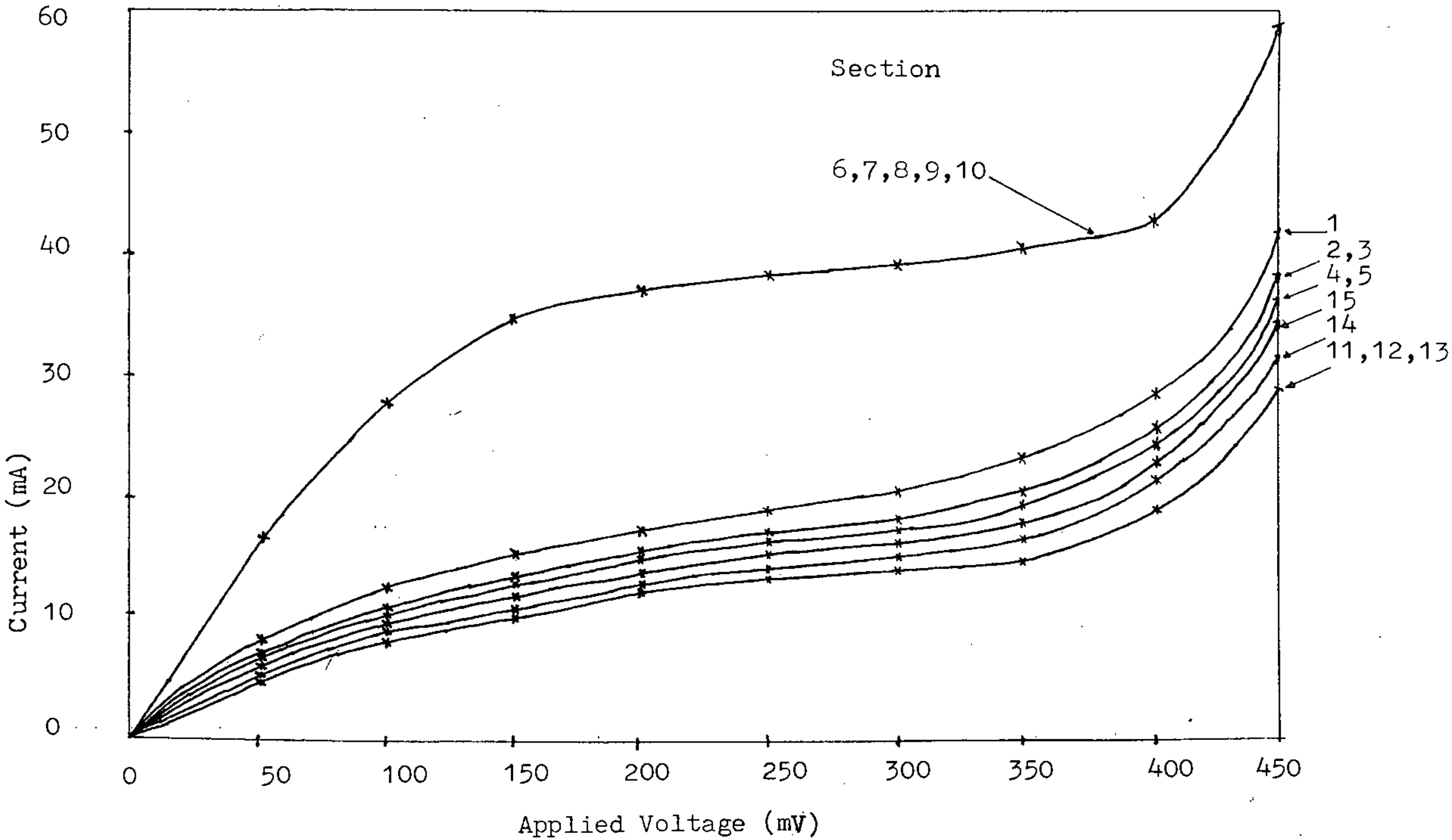
The individual current on different sections of the cathode was measured at different flow rates by a progressive step increase in applied voltage of 50 mV until all the sectioned element attained and exceeded their limiting current. The data obtained is shown in the Appendix C. From this data the current voltage curves were plotted. Both the sectional and overall currents against applied voltages are shown in figures 4.1 and 4.2. The limiting current value was obtained from the current plateau or the point of inflection on the current voltage curve. In this study all the results have been calculated from the limiting current condition, because operational limiting current implies the maximum mass transfer. By repeating a number of runs, the reproducibility of the data was checked and it was within the accuracy of about 5%..

4.2.1 Current Voltage Curve:

Figure 4.1 shows typical individual sectional current against applied voltage and figure 4.2 stands for total current against applied voltage at different flow rates. Both these curves are in good agreement with those obtained by others like Fukunaka Y., Doi H., and Kondo Y. [13] who worked on rectangular cells. The current and hence the current density at the cathode increases with the increase in the cathodic overpotential. The concentration of Cu^{++} ions starts decreasing with the increase in the cathodic overpotential in the initial region of the curve. So the concentration gradient started increasing and hence the mass transfer also increased. Since the whole reaction is mass transfer controlled the reaction rate increases. This is why the currents showed an increasing tendency in this region.

In the middle region of the curve the rate of increase of current slowed down significantly and became constant in most cases. This is due to the fact that with increase in the potential a point is reached when the concentration of Cu^{++} ion at the cathode gets a value of about zero. Here concentration gradient, mass transfer rate, and current become constant.

Figure 4.1: Current Vs. Applied Voltage for Individual Section



After this region, the current increased rapidly. In this region the evolution of H_2 starts with excessive loss of current. The reaction is as follows:

$$2H^{+} + 2e^{-} = 2H \longrightarrow H_2$$

This can be compared with the result obtained by Fukunaka Y., Doi H., and Kondo, Y. [13]. They observed that for 0.05 M $CuSO_4$ solution the concentration of Cu^{++} at the cathode was about 0.24 M/dm^3 at 43 mV. But this value decreases with increasing cathodic overpotential. At about 150 mV the concentration reached the value of about zero and the inflection point was about 155 mV.

However from their observation of interferometry, they came to the conclusion that the limiting current density is realized at a slightly higher location above the inflection point of the current -voltage curve.

It is evident from the figures that there is a distinct limiting current plateaus on each curve for each flow rate of the electrolyte and these plateaus are well defined and wider for lower flow rates and less defined and less wider for higher flow rates. At higher flow rate the limiting current plateau reduces to an inflection point only. The limiting current plateau was in the range of 250 mV to 400 mV. The shrinkage and the shift of limiting current plateau in the higher voltage region occur with increased flow rates. With increased flow rates the limiting current density increases. This may be due to the reason that with increased agitation at this conditions higher local current densities may result which form a very crystalline or poor electrodeposits. This increases the effective electrode area. Increased area results in higher mass transfer rate. Thus the current density increases with flow rate. This may be due to the reason that the rough deposits are able to catalyze the formation of gas at lower potential giving rise to early current plateaus. With very high flow rates the particle becomes so dispersed that the fluidization effect tends to decrease the limiting current and the mass transfer rate.

From figure 4.1, it is clear that the limiting current plateau on all the segments starts and ends at the same potential. It can also be observed that the variation of current in some sections e.g. sections 11-14 and section 2 and 3 are more or less similar. This is because these sections occupy hydrodynamically similar positions in the cell.

In figure 4.1, it is seen that the sections 6,7,8,9,10 have higher value of limiting current. These sections have area four times larger than that of any other section of the cathode. Larger area permits more Cu^{++} ions to be deposited. Hence these sections exhibit higher limiting current.

Among the sections of the cathode the first attains the highest value of limiting current and then it decreases. It increases again in the exit section. Sections 2,3,4,5,11 and 12 has more or less similar limiting. Sections 12 and 13 have same i_L. Section 14 has a little higher value than that of sections 12 and 13 and section 15 has much higher value. This higher value of limiting current at the inlet section of the cell is due to the entrance effect, the change in shape and size of the flow area, the complexity of hydrodynamic conditions such as secondary flow and back mixing, eddy effect, separation and reattachment of the flow after sudden expansion. These effects the first section to have a higher limiting current. This agrees with the study of Krall and Sparrow [20], Runchal and Wragg [36] and Tagg and Patric [42] who had obtained a region of maximum mass transfer rate at a distance of 1.5 to 2.5 times the equivalent diameter of the large duct down stream from the leading edge of the electrode. The point of maximum mass transfer coefficient has been taken as the point of reattachment. It then starts decreasing through section 2,3,4 and 5. On sections 6 to 10, it gets the minimum and stable value of current density. Hence the limiting current at the middle section of the reactor is approximately constant. This may be due to the equal agitational effect of the fluidized bed. The limiting current increases gradually again through the exit section. This is caused by the turbulence generated by the sudden decrease in flow channel area at the exit of the cell.

Figure 4.2: Total Current Vs. Applied Voltage for Different Electrolytic Flow Rate

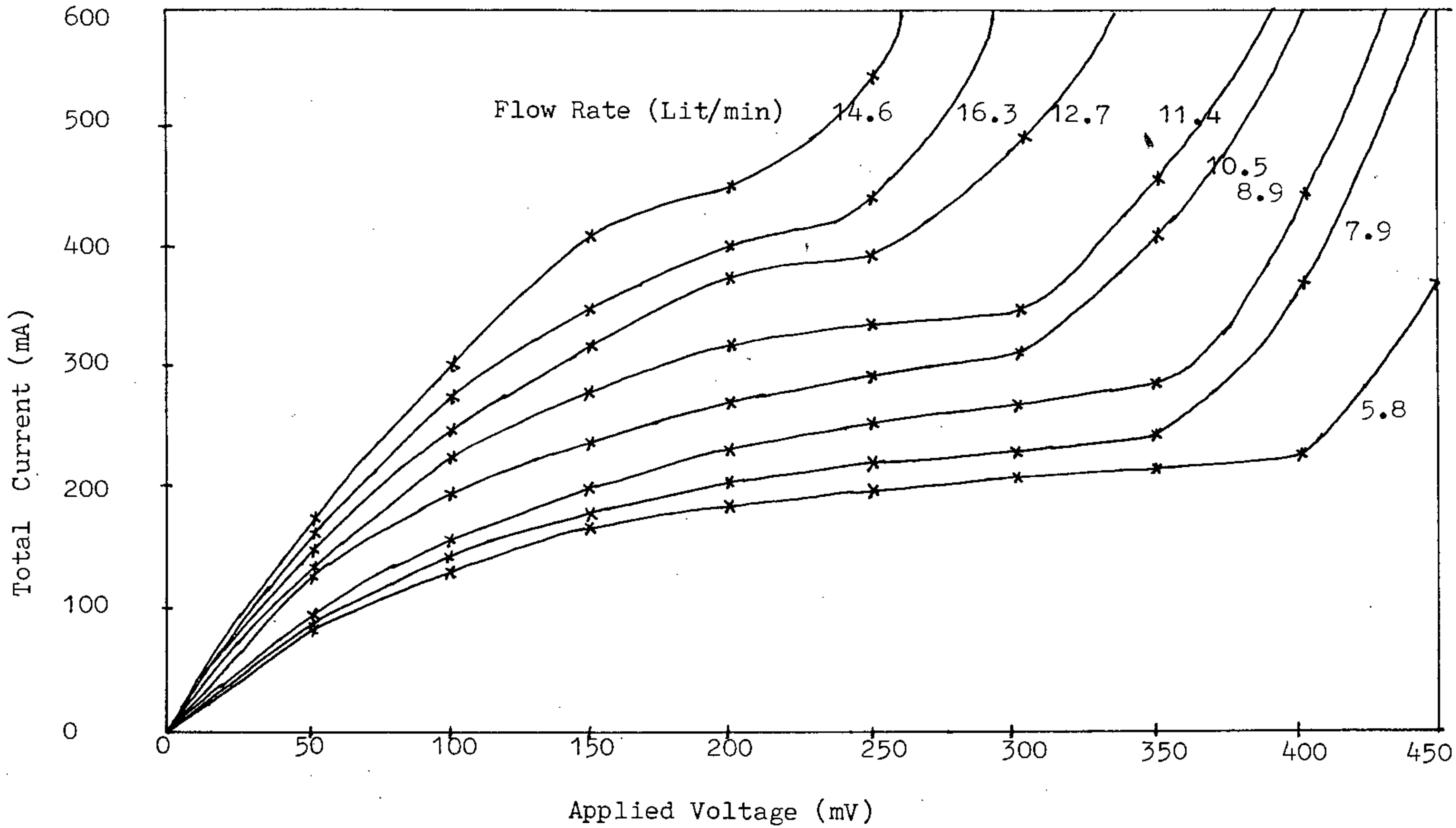


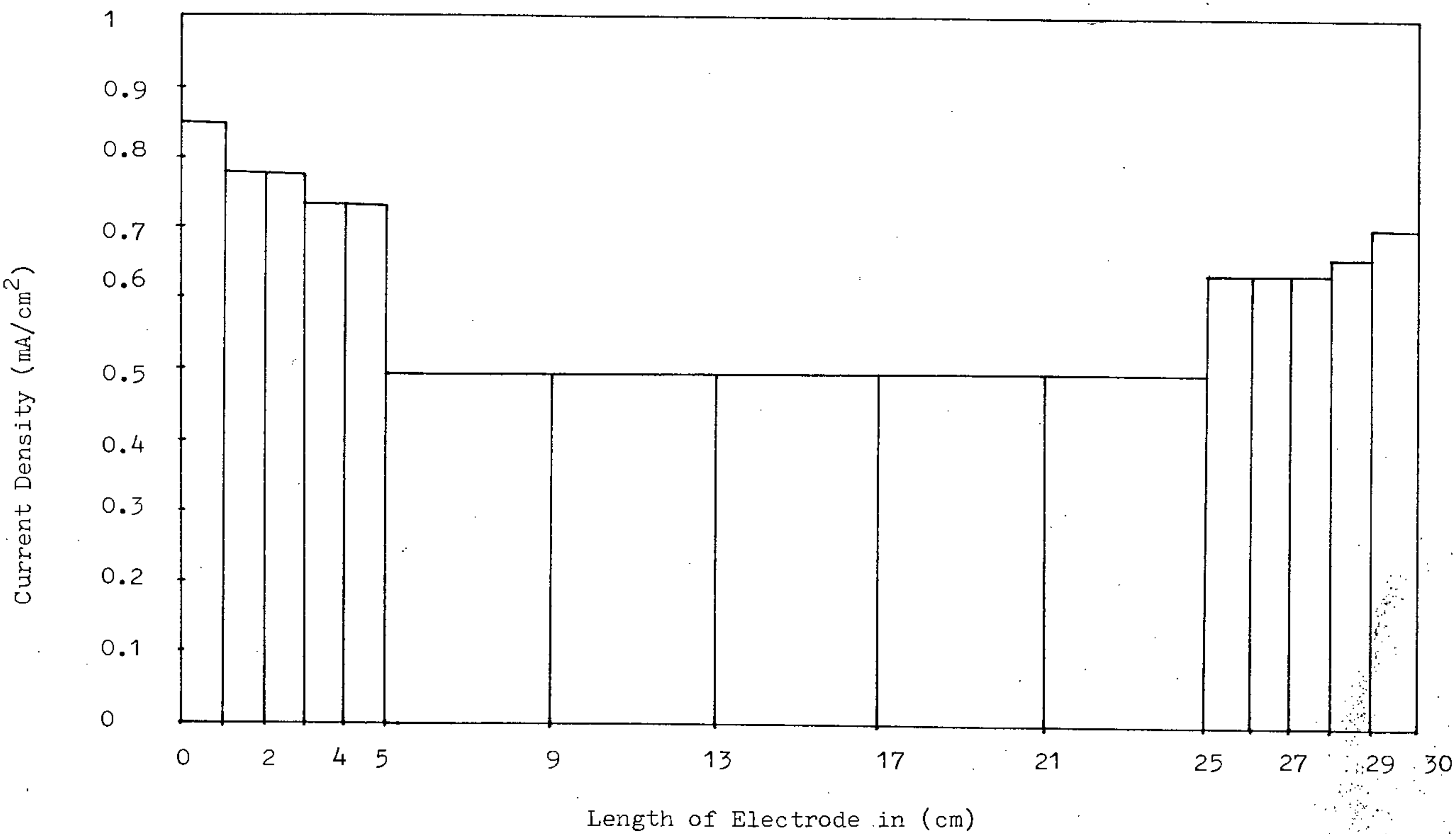
Figure 4.2 shows the variation of total current against applied voltage at different flow rates. It can be seen from this figure that for the same amount of applied voltage the current is higher for higher electrolyte flow rate. With increase in the flow rate of the electrolyte the agitational effect and momentum transfer increase. Higher momentum transfer increases the charge transfer rate and ultimately the amount of current increases. It increased upto the flow rate of 14.6 lit/min. At flow rate 16.3 it decreased again. This is because at such higher velocity the particles are so dispersed the overall situation decreases the mass transfer rate.

4.2.2 Current Distribution Along The Length The Electrode:

For comparison it is useful to compare current distribution along the length of the electrode at limiting current conditions because a stable current distribution is reached with sum of individual sectional currents equal to the total measured current. Moreover, from the current voltage curve, it can be seen that the limiting conditions starts at the same time for all the sections of the electrode.

Figure 4.3 shows the variation of current density along the length of the cathode at limiting current condition. It has been graphically represented in the form of histograms. This figure 4.3 shows the current density at different sections of the electrode at limiting current conditions. Figure shows that the first and last sections are exhibiting highest current density. Sections 2-5 and 11-14 are exhibiting similar current density and section 6-10 are exhibiting similar current density that is different from that of any other sections of the electrode. The fraction of current passing through each section of the electrode has been calculated from current voltage data at different fluid flow rates. For a given fluid flow rate, the fractional current passing through an individual section is approximately constant irrespective of any applied voltage whether the reactor is operating below, at or above limiting current conditions. From figure 4.3, it can be seen that there is an increase in current density at the inlet and exit sections of the cell. This is due to the developing

Figure 4.3: Current Density Along the Length of Electrode



velocity and concentration profiles in the boundary layer at the entrance and due to the effect of accelerating velocity gradients in the exit sections of the electrode.

The middle section has an approximately stable current density because this section is free from any expansion or contraction effect. In this region the construction of cell is uniform. Solid particles forces uniform impulsive effect at the cathode. Here electrolyte velocity is fully developed and solid particles are uniformly distributed. This results in the uniform distribution of the Cu^{++} ions.

This supports the observation of Takehara K. and Takehara H [43]. In their experimental study they found by x-ray photography that the accumulation of ions in the middle section is always uniform. But that at the entrance and exit sections are not uniform.

4.2.3 Mass Transfer Coefficient Along The Length Of The Electrode.

Variations in the individual mass transfer coefficient over the sections can, of course, be obtained by the plots of the current distribution along the length of the electrode as shown in figure 4.3. It shows slight enhancement of mass transfer at the inlet and exit section in comparison with the middle region (the middle five sections). This is due to the entrance and exit effect. At the entrance, expansion with substantial eddy formation happens. This eddy flow of the electrolyte enhance mass transfer. At the exit section, contraction takes place and the solid particles reverse its flow direction. These two effects enhance the mass transfer rate. This means that mass transfer coefficient is independent of distance due to uniform agitation resulting from the fluidization of glass beads if the cell construction is uniform and flow is fully developed throughout the cell.

In their study, Gendron and Ettel [14] obtained the highest mass transfer coefficient at the leading edge of the electrode and this then decreased after first fifteen centimeters. But an almost uniform distribution was achieved after 15 cm with a very slight decrease in mass transfer coefficient along the length of the electrode. Their study can be compared with the present study that higher mass transfer coefficient is obtained at the first five sections. The mass transfer at the next sections (next 20 cm) is constant and there is a slight increase in mass transfer coefficient at the last five sections.

This also be compared with the study of study of Takehara K. and Takehara H (43). They obtained uniform ion distribution along the length of the cathode in the middle region and the uniformity was irrespective of the distance from the leading edge of the electrode.

4.2.4 Variation Of Cumulative Average Mass Transfer Coefficient Along The Electrode Length:

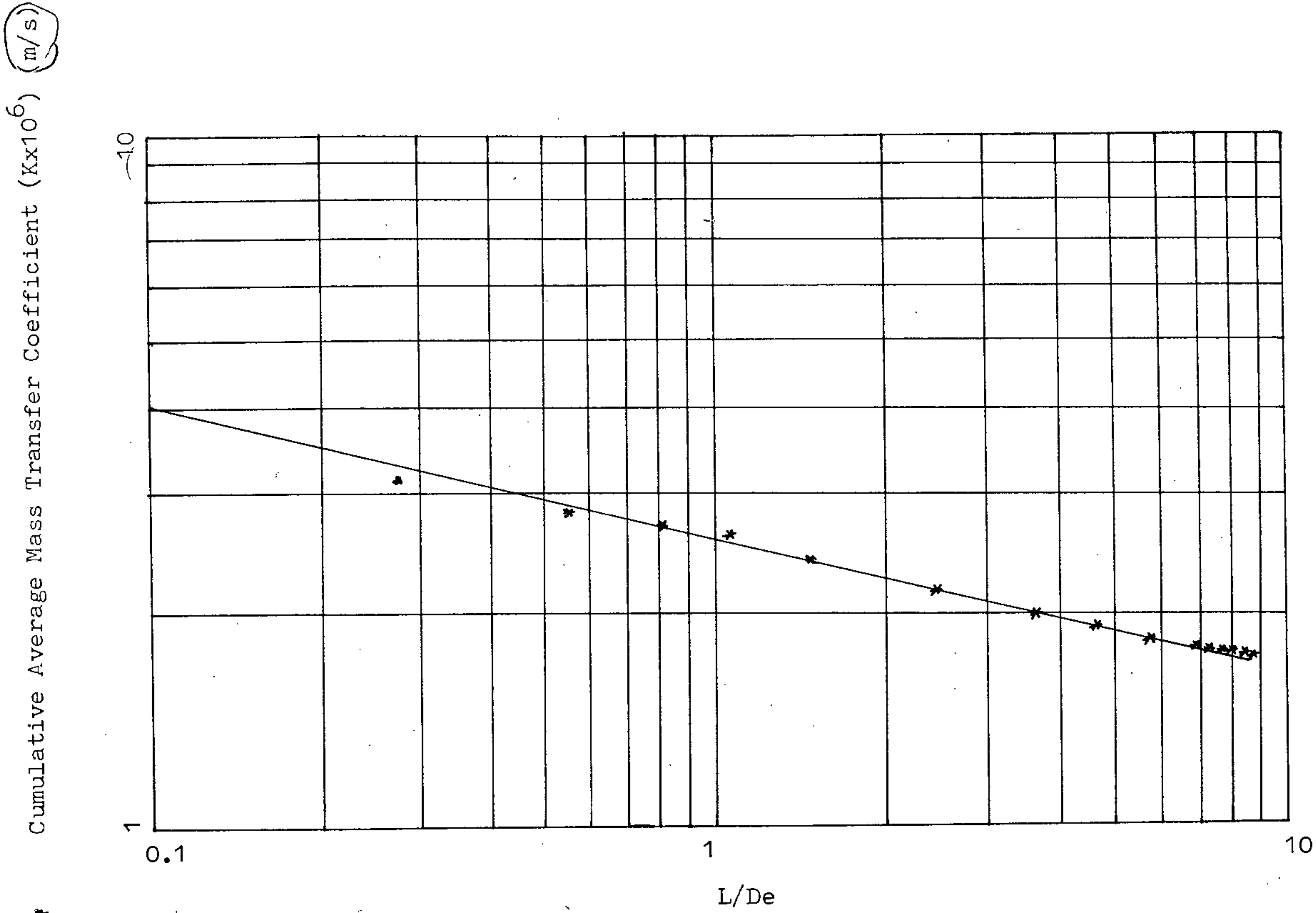
In Fig. 4.4 cumulative average mass transfer coefficient (k_{cav}) has been plotted against L/De in logarithmic scale. Although it has been shown by histograms in the previous sections that current density almost constant in the middle regions of the cell, but current density varies at the inlet and exit sections. This means that rate of deposition at middle section is uniform and due to sudden expansion at the inlet and contraction at the exit there is entrance and exit effects only. If a continuous cathode is used, mass transfer along the cathode length will be influenced by the inlet and the exit effects. Cumulative average mass transfer coefficient is highest at the leading edge of the electrode. It then decreases as the distance from the leading increases. Finally the mass transfer coefficient increases at the exit sections due to exit effect.

Figure 4.10 shows that the cumulative average mass transfer coefficient is related to L/De ≥ 10.0 by the equation of the form

$$K_{cav} \propto (L/De)^{-0.2}$$

The above findings can be compared with the correlation for rectangular duct obtained by Pickett and Ong [26] upto L/De ≥ 12.5 as,

Figure 4.4 : Cumulative Average Mass Transfer Coefficient Vs. L/De



$$K_{cav} \ \alpha \ (L/De)^{-0.2}$$

The exponent on the L/De term was obtained by Vanshaw et al. [46] as -0.3 for the turbulent flow. M. S. Ali [1] found the value of the exponent in the range of -0.33 to -0.16. The lower value of the exponent in the present study is probably due to fluidization that imparts increased agitation and thereby ensures better mixing. Up to L/De = 1 the variation of mass transfer coefficient is less due to entrance effects.

4.2.5 Variation Of Mass Transfer Coefficient With Superficial Electrolyte Velocity

Figure 4.5 and 4.6 shows the variation of mass transfer coefficient with superficial electrolyte velocity for different particle sizes 1 mm and 2 mm respectively. From this figure it can be observed that with increasing fluid velocity the mass transfer coefficient increases initially but at some fluid velocity the maximum value of mass transfer coefficient is reached and after this it starts decreasing. This is because with increase in the electrolyte velocity, the velocity of the fluidized particles increases. It enforces the copper ions to move to the cathode with higher momentum. This increases the mass transfer rate and thus the mass transfer coefficient increases. Moreover higher velocity takes part in increasing the mass transfer coefficient by higher agitational effect. It can be seen that the maximum mass transfer coefficient lies in the range occurs at around 6 cm/s for 1 mm and 2 mm particles. For 3 mm Particles it is higher than 6.8 cm/sec superficial electrolyte velocity. It can be compared with the result of Gomes E.[15] who obtained the highest mass transfer velocity to be 13.5 cm/s. Results can be compared with that of Coeuret and Goff [11] who come to the conclusion that for particle of diameter 0.6 to 2.0 mm the maximum mass transfer can be obtained with the electrolyte velocity of 4-8 cm/sec. Gomes E. compared his result with that of Walker and Wragg [48] and Coeuret and Goff [11]. He reached to the conclusion that the velocity at which maximum mass transfer occurs increases with increase in particle size. For the same amount of agitation larger particles

Figure 4.5 Relationship Between Superficial Electrolyte Velocity and Mass Transfer Coefficient at Different Bed Height for Particle of 1 mm

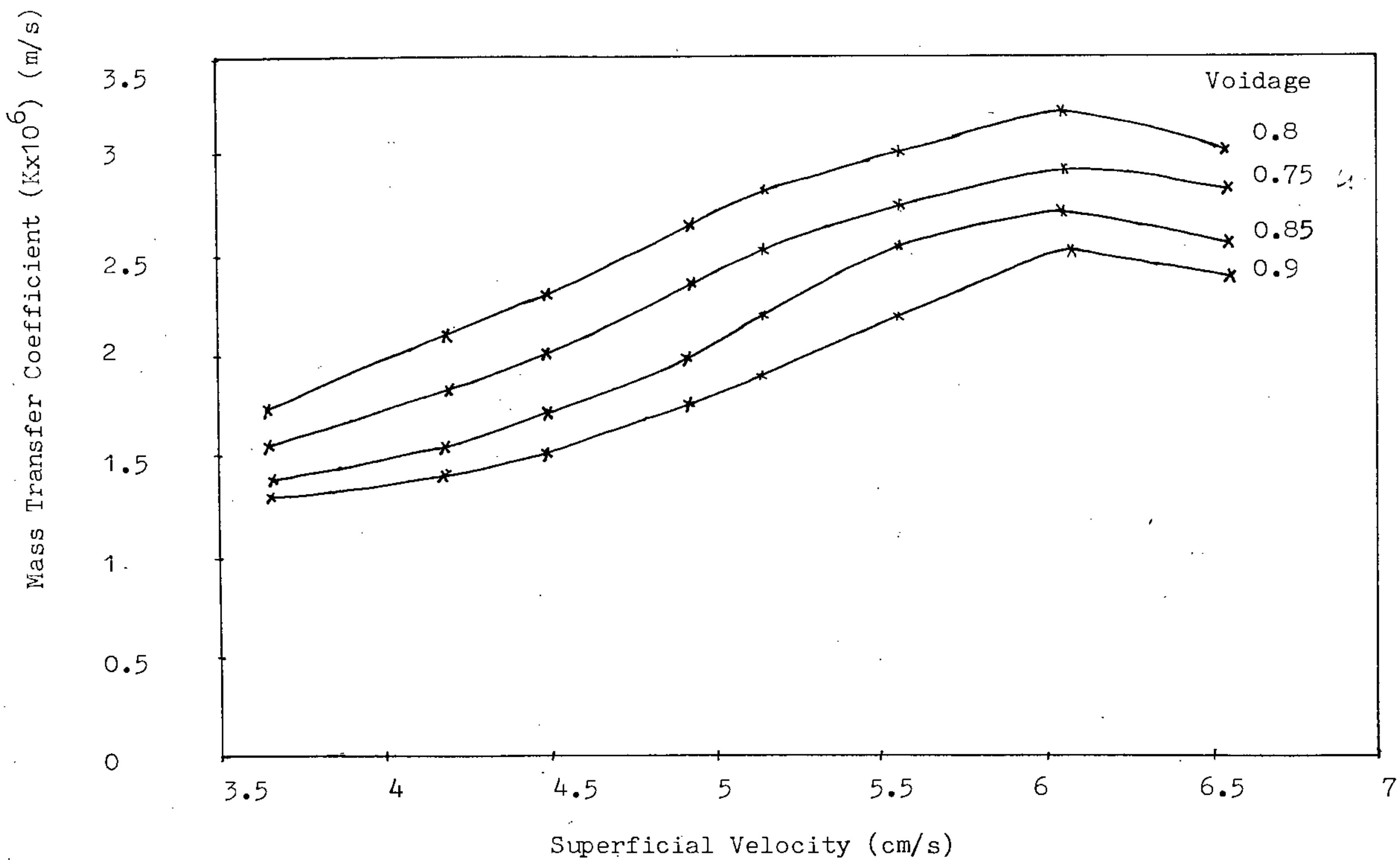
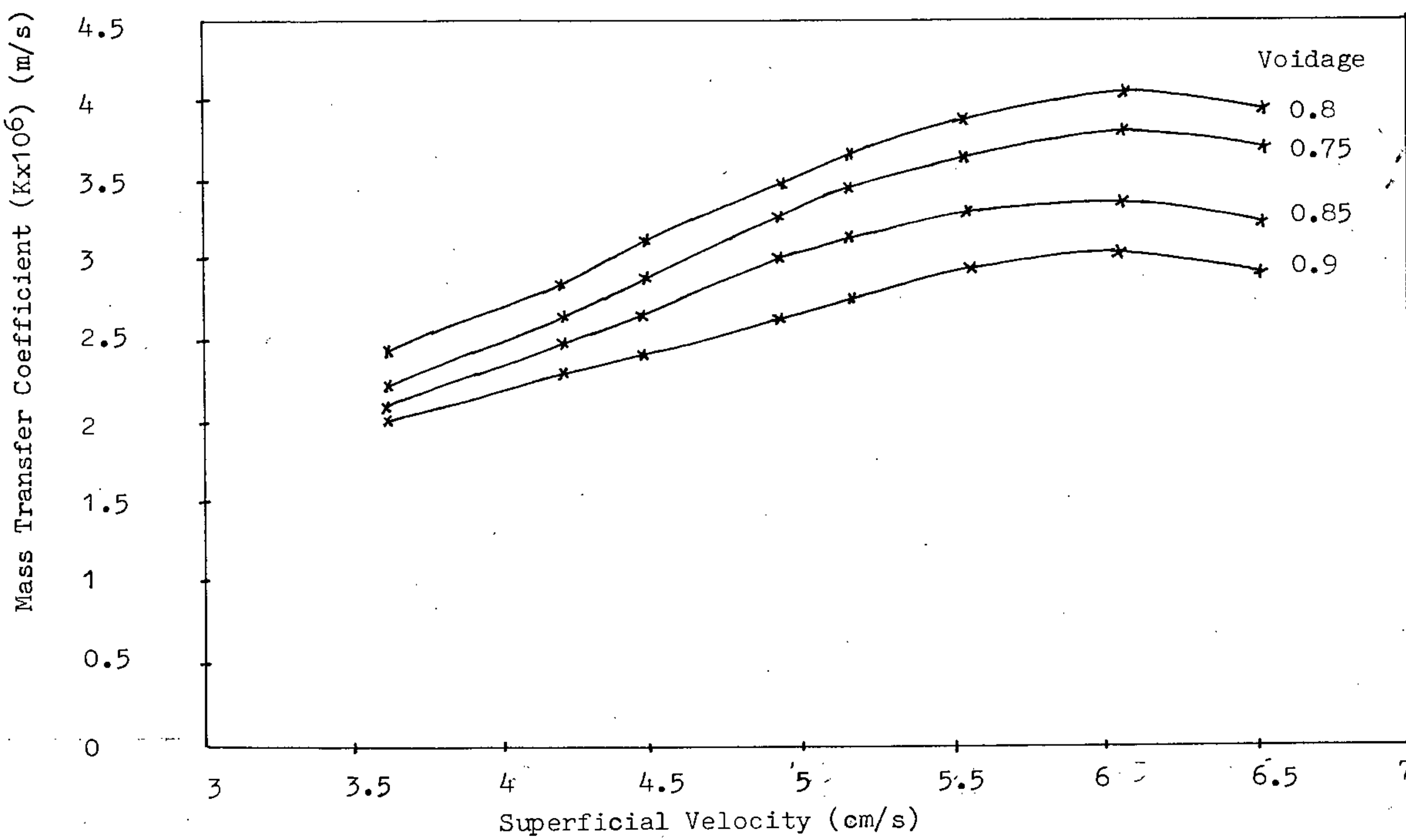


Figure 4.6 : Relationship Between Superficial Electrolyte Velocity and Mass Transfer Coefficient at Different Bed Height for Particle of 2 mm



require higher superficial velocity. Present study also supports the results of the workers mentioned above.

Figure 4.5 and 4.6 implies that after the maximum mass transfer velocity is reached, increasing electrolyte velocity decreases the mass transfer coefficient. This is because at very high velocities the fluidizing particles become so dispersed that the fluidizing effect starts to disappear and the two effects super-impose each other. As a result mass transfer coefficient decreases. Walker and Wragg [48] studied the aspect of fluidized bed electrochemical reactor and they found the maximum value of mass transfer coefficient, k, at superficial velocity u = 1-3 cm/s for particle sizes of 0.275 to 0.548 mm. Coeuret F. and Goff L. [11] also found the maximum value of k at superficial velocity u = 4-8 cm/s for particle sizes of 0.6 to 2.0 mm. Gomes E. [15] obtained the maximum value of k at superficial velocity u = 13.5-15.5 cm/s for particle sizes of 3.0 to 6.0 mm.

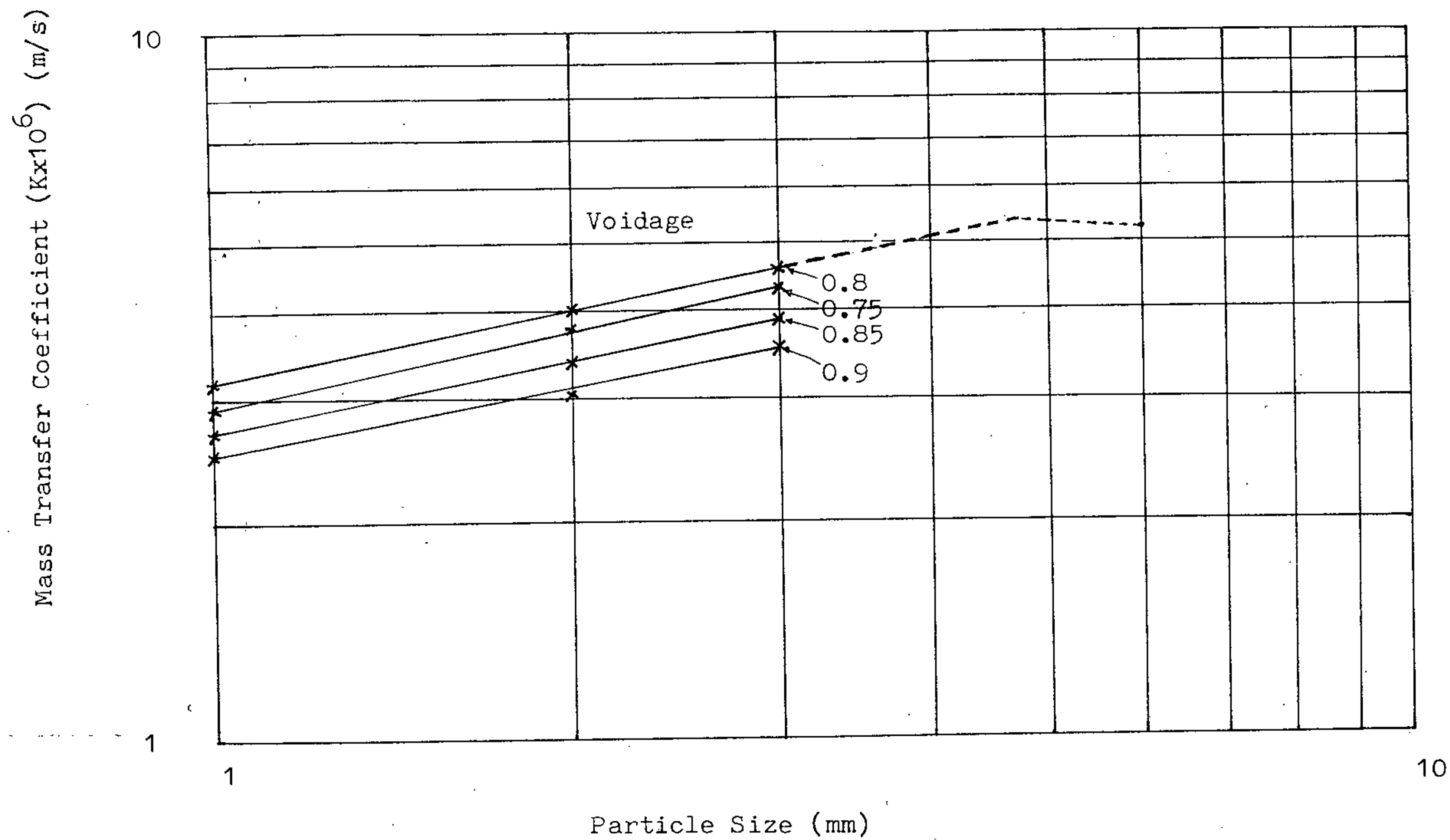
The result of previous workers together with the present one is given below in tabulated form.

Author	Maximum mass transfer velocity u (cm/s)	Particle size (mm)
Walker and Wragg [48]	1-3	0.275-0.548
Coeuret F. and Goff L [11]	4-8	0.6-2.0
Gomes E. [15]	13.5-15.5	3.0-6.0
Present Study	Around 6.0 Above 6.8	1.0-2.0 3.0

4.2.6 Effect Of Particle Size On Mass Transfer Coefficient:

Figure 4.7 shows the effect of particle size on mass transfer coefficient. Mass transfer coefficient is smallest for the 1 mm particle and it increases with the increase in the size of the particle. The increase of particle size is due to the bubble formation in the fluidized bed for the larger particles. In this study three different sizes of particles (1 mm, 2 mm and 3 mm) are used and Froude numbers, Fr ($=U^2_{mf}$ / gd), are calculated for three particle sizes are, 0.18, 0.25 and 0.33 respectively. As mentioned earlier, Wilhelm and Kwauk [49] suggested that Froude number as a criterion for the bubble formation. They worked with particles of different sizes. According to them, for Froud number larger than one, bubbles should be observed. In fact, significant bubbles could not be observed for these particle sizes. From the figures, it can be observed that the mass transfer coefficient is lowest for smallest particle size (1.0 mm) and for particles sizes of 3.0 mm the mass transfer coefficient is highest. With the increase of particle size, the agitation caused by the particle movement in the cell become more vigorous and hence current density as well as mass transfer rate increases. Gomes E [15] combined his experimental results with that of Wilhelm and Kwauk [49] and came to the conclusion that the mass transfer rate increases with the increase in particle size upto 4.5 mm particle. Further increase in particle size, the particles become heavier and the agitation to the electrode decreases and hence current density as well as mass transfer rate decreases. Also with 6.0 mm particle size, vigorous bubbling occurred in the cell and pockets of liquid passes through the cell without proper mixing and this might contribute to the decrease of the current densities and mass transfer coefficient.

Figure 4.7 : Mass Transfer Coefficient Vs. Particle Size at 14.6 Lit/min Flow Rate



4.2.7 Variation Of the Mass Transfer Coefficient With Different Initial Bed Height

Variations of the current distribution along the electrode length have been observed for different initial bed height. Figure 4.8 and 4.9 shows the variation of mass transfer coefficient with different initial bed height. The initial bed heights of 6.0 cm, 9.0 cm, 12.0 cm and 15.0 cm are used. Mass transfer coefficient increases with the increase of initial bed height because uniform agitation can be obtained with the increase in bed height. Moreover with increase in initial bed height large numbers of particles take in the momentum transfer to the electrode. Thus the mass transfer rate increases. This increases upto the bed height of 12 cm. But further increase in bed height the mass transfer rate decrease. This is due to the increase in bed height the voidage the electrolyte transfer in the cell decreases because the total cell volume remains constant. So the displacement of electrolyte to the electrode does not get enough free space for movement and the overall mass transfer decreases.

4.2.8 Variation Of Mass Transfer Coefficients With Bed Voidage

Figure 4.10 and 4.11 shows the variation of the mass transfer coefficient with bed voidages for different particle sizes 1 mm and 2 mm. For all the three particle sizes, it is observed that the maximum value of mass transfer coefficient occurs at voidage around 0.8. Walker and Wragg [31] studied mass transfer rate with much smaller glass particles (0.274 ~ 0.548 mm) and their data exhibited a maximum value of mass transfer coefficient at voidage ε = 0.7 ~ 0.75. From several studies Walker and Wragg [31] concluded that the maximum value of mass transfer coefficient in the voidage range of 0.7 to 0.81 occurs because the kinetic energy imparted by the particles are maximum in the above voidage range. Maximum kinetic energy imparted by the particles to the electrode and maximum mass transfer rates are closely related. Puiggene J., Larrayoz M.A. and Marty A. [28] have plotted curves showing the relation of mass transfer coefficient vs. electrolyte velocity and voidage vs.

Figure 4.8 : Relationship Between Initial Bed Height and Mass Transfer Coefficient at Different Electrolyte Velocity for Particle of 1 mm (Dia)

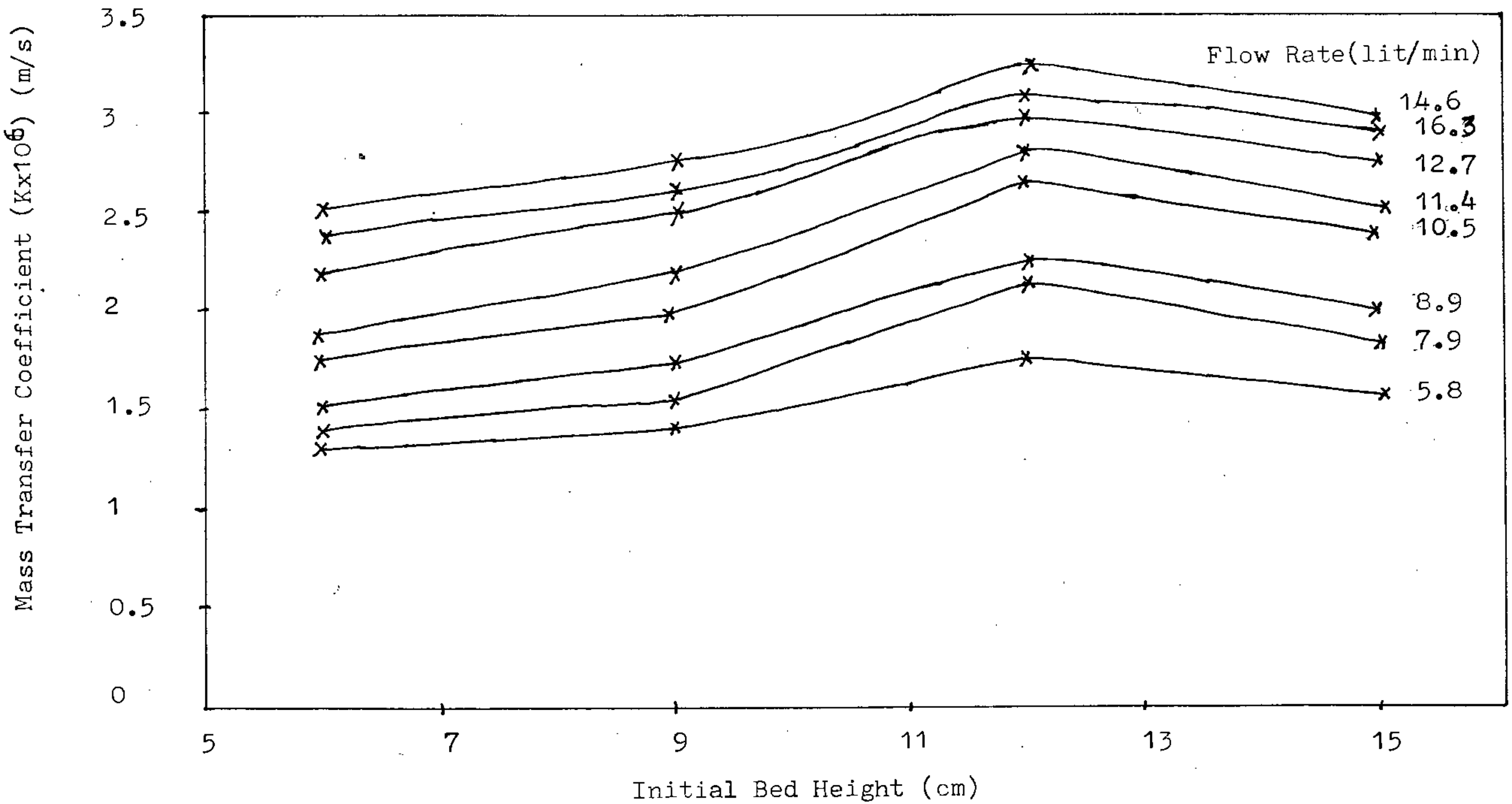


Figure 4.9: Mass Transfer Coefficient Vs. Initial Bed Height

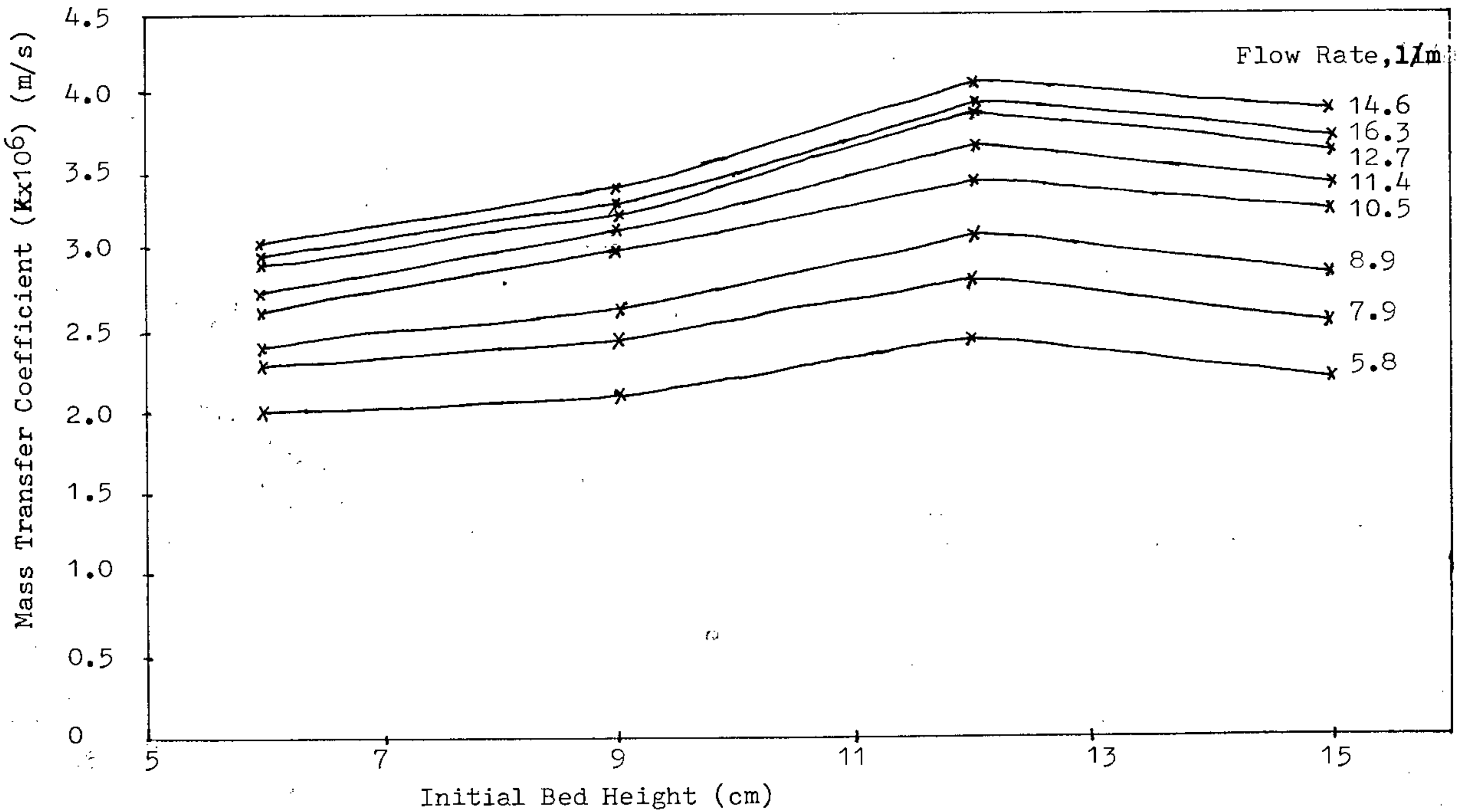


Figure 4.10: Mass Transfer Coefficient Vs. Voidage for 1 mm(dia) Particle

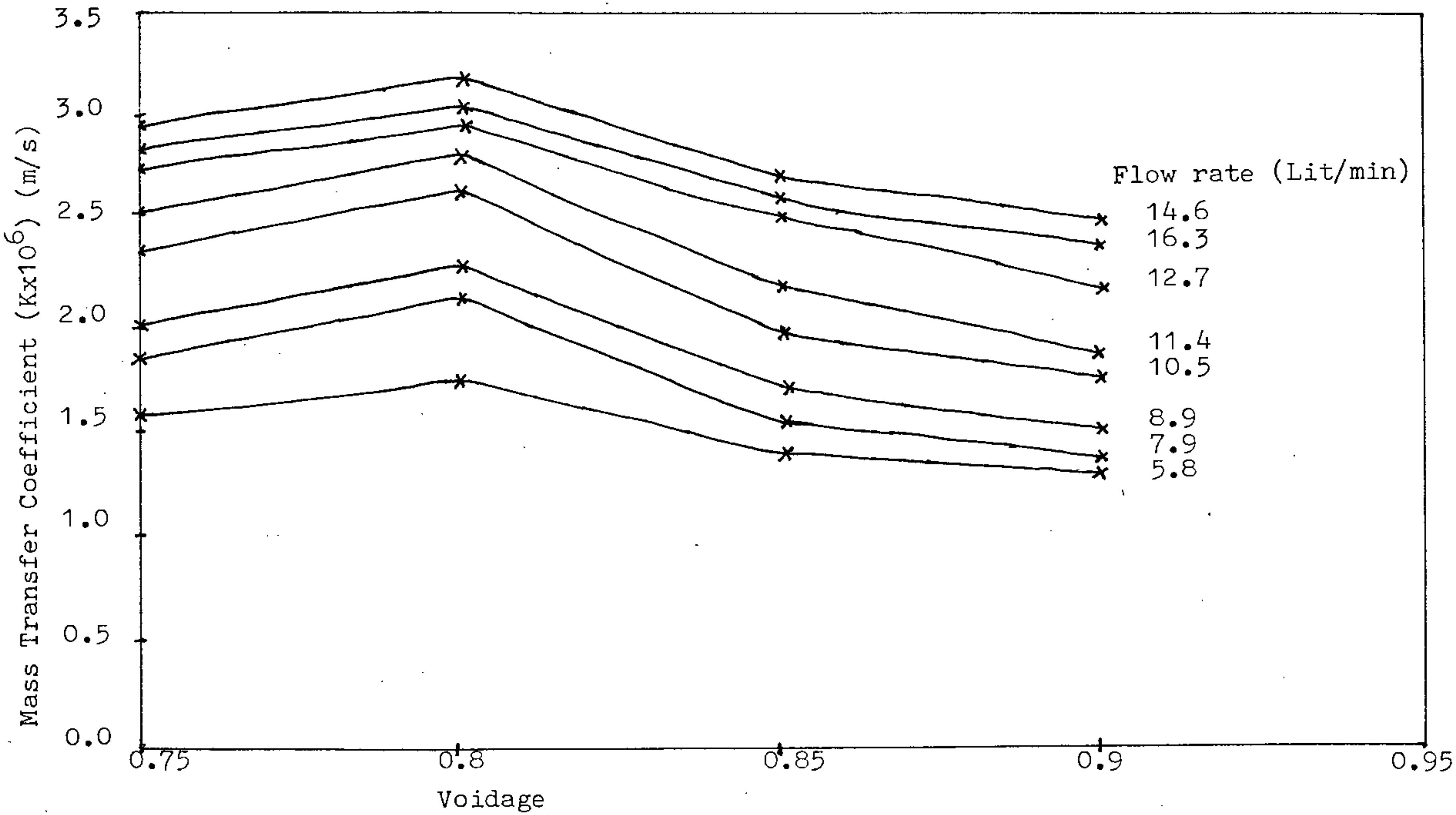
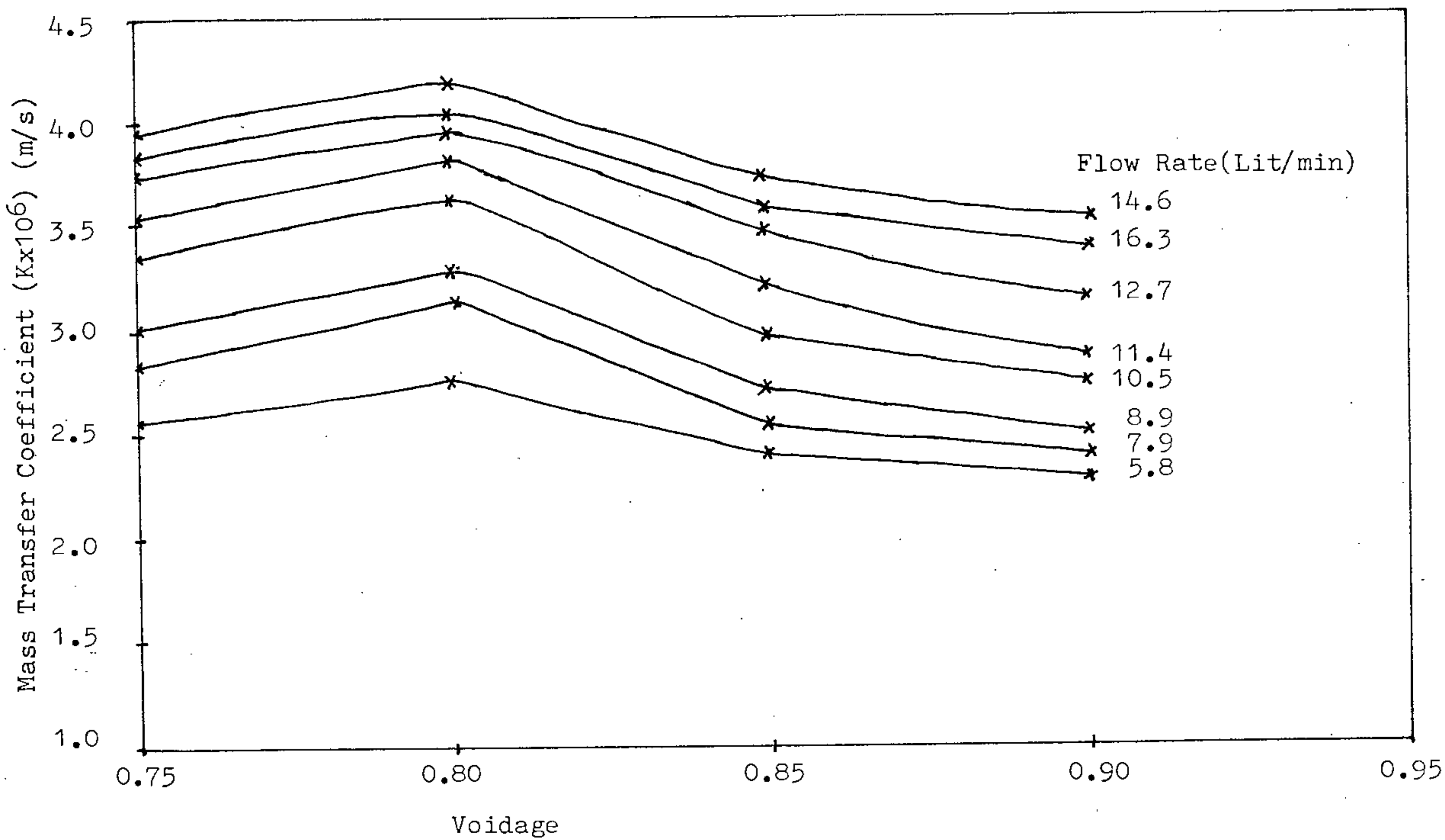


Figure 4.11 Mass Transfer Coefficient Vs. Voidage for 2 mm (dia) Particle



fluid velocity. They obtained that the maximum mass transfer rate and the maximum voidage occurred at the same velocity and the maximum voidage was about 0.78. That is they obtained the maximum mass transfer at the voidage of about 0.78. Gomes E. obtained the maximum mass transfer voidage 0.81 for 3.0 mm particle and 0.82 for particles 4.5 mm and 6.0 mm diameter.

Smith and King [39] from their experimental results concluded that the value of voidage at which the maximum mass transfer occurs increases with the increase in particle size.

This implies that the present study is in quite agreement with the above mentioned author.

4.2.9 Overall Mass Transfer Correlation:

From figure 4.12, 4.13 and 4.14 the relationship between Sherwood Number and Reynolds number can be obtained for particles of 1 mm, 2 mm and 3 mm diameter respectively. It can be seen from the figures that the slopes are o.8, 0.5 and 0.4 for 1 mm, 2 mm, and 3 mm diameter particles respectively.

The following relations can be obtained:

$Sh = a\,Re^{0.8}$ where $a = 0.10\ \varepsilon_i/\varepsilon$ For 1 mm diameter particle

$Sh = a\,Re^{0.5}$ where $a = 0.12\ \varepsilon_i/\varepsilon$ For 2 mm diameter particle

$Sh = a\,Re^{0.4}$ where $a = 0.17\ \varepsilon_i/\varepsilon$ For 3 mm diameter particle

The value of the slope decreases with increase in particle size. This indicates that, for smaller particle, the effect of movement of electrolyte to the wall is more pronounced and more turbulence is created and for larger particles this effect decreases giving rise to uniform distribution of the deposit. That is, with particles of larger diameter the uniformity of mass along the length of the electrode can be obtained.

Figure 4.12: Sherwood Number Vs. Reynolds Number for 1 mm (dia)Particle

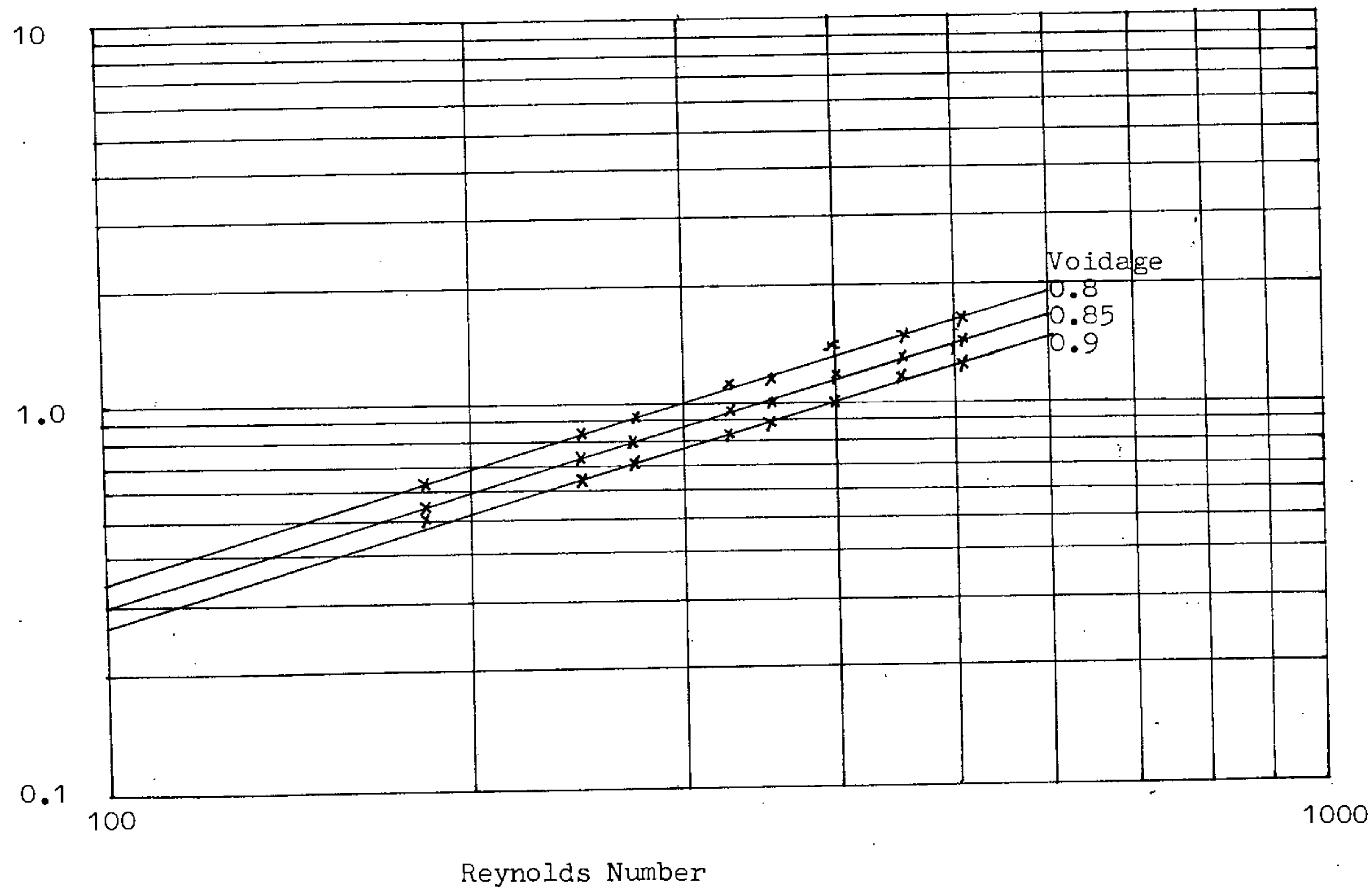


Figure 4.13: Sherwood Number Vs. Reynolds Number for 2 mm (dia) Particle

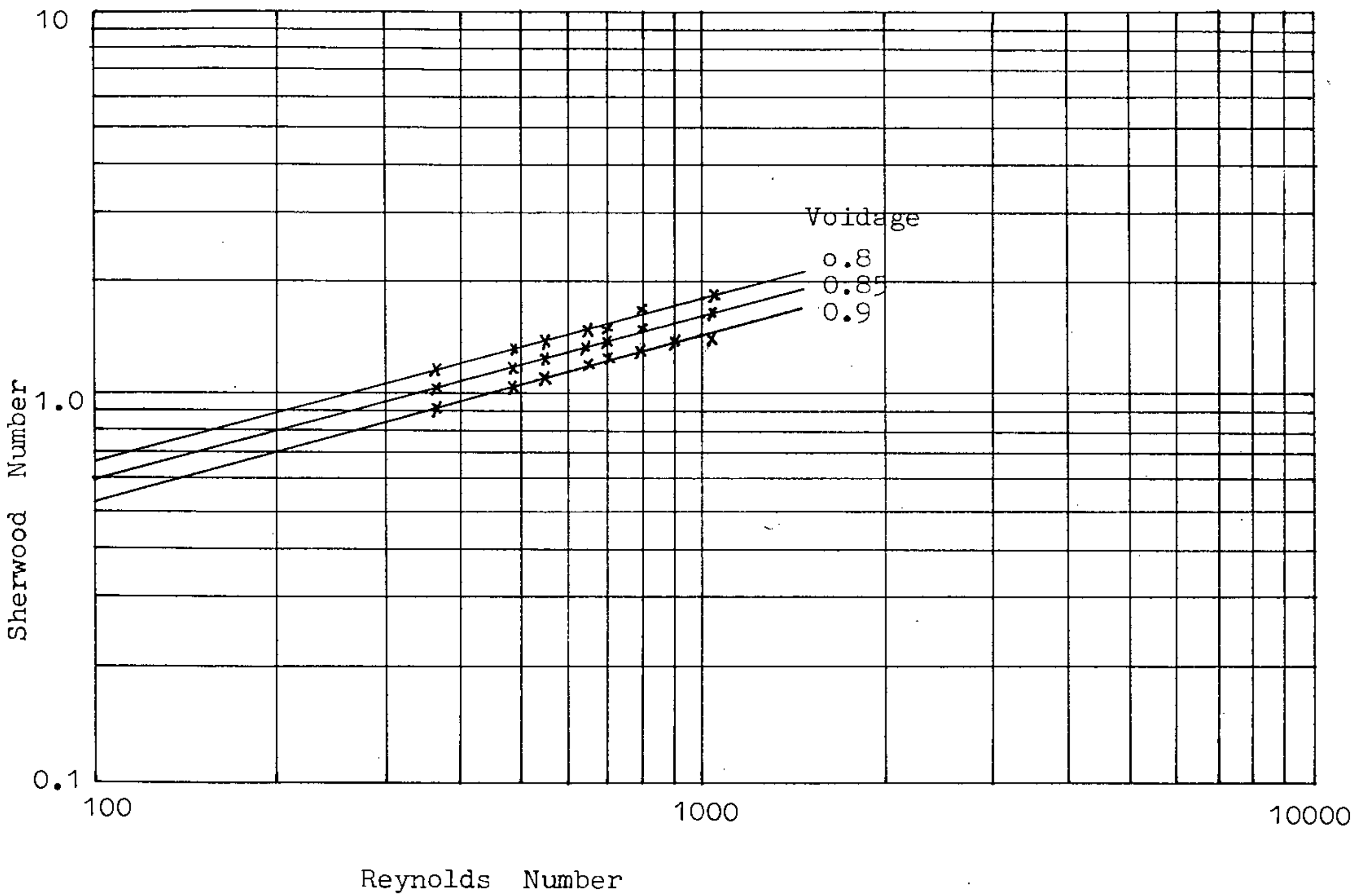
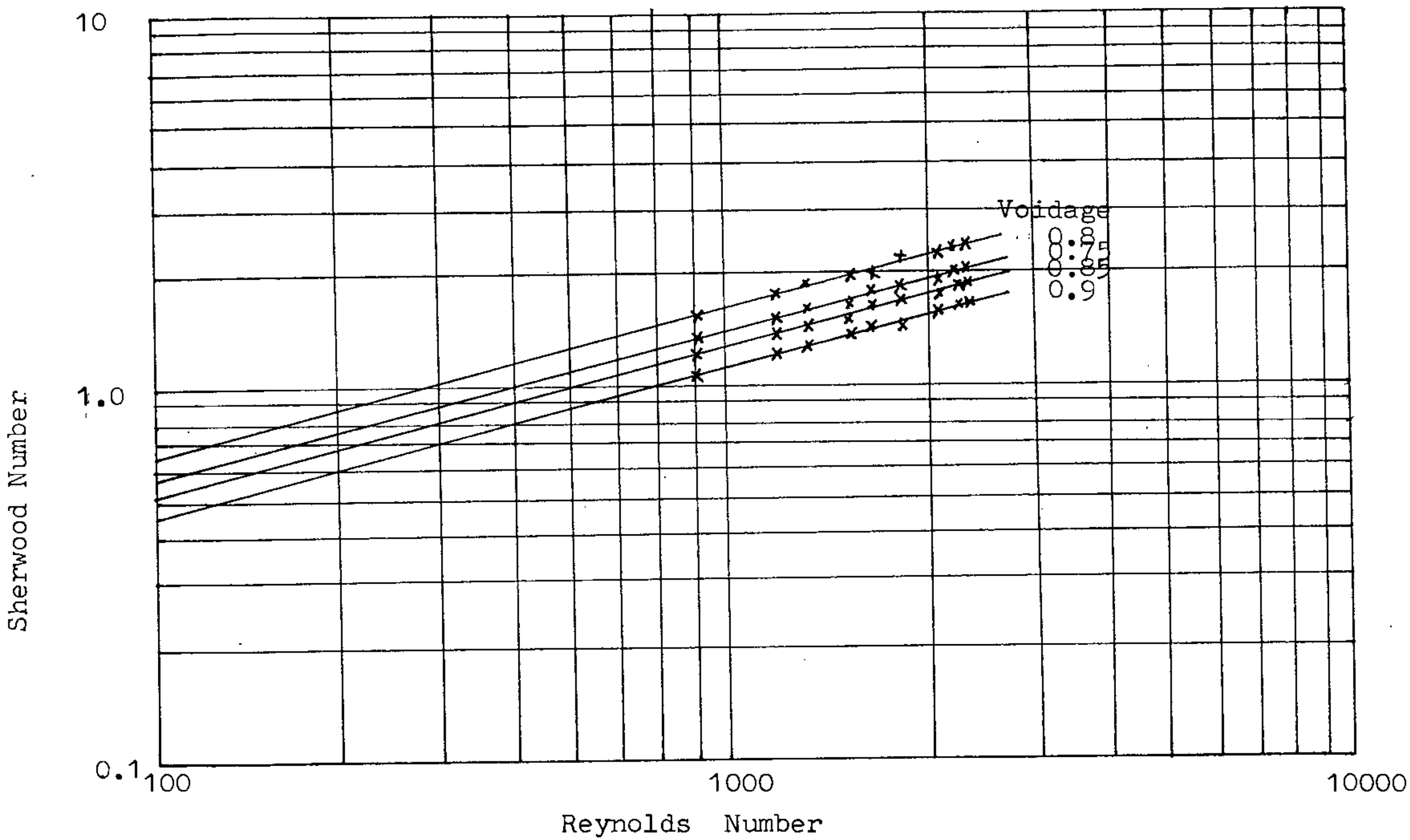


Figure 4.14: Sherwood Number Vs. Reynolds Number for 3 mm (dia)Particle



It is apparent that for particles of 1 mm diameter the value of the exponent on Reynolds number is 0.8 that indicates the value of the exponent during axial flow. In the case of smaller particles the contribution on mass transfer is the same as that without any particle. As the particle diameter increases, the influence of axial flow on the mass transfer decreases.

It can be seen that the value of 'a' is higher for larger particles. In the previous discussion it has been shown that the mass transfer rate is higher for larger particle. That is the value of a has a significant role on mass transfer coefficient and a is dependent on the diameter of the particle. Hence attempt has been taken to correlate a with particle diameter and the following empirical correlation is obtained:

$$a = 0.14\,(d_p\varepsilon)^b\,\varepsilon_i/\varepsilon \quad \text{Where} \quad b = 10\,d_p/De$$

d_p = particle diameter, mm

De = equivalent diameter, mm

ε_i = voidage before fluidization

ε = voidage after fluidization

When the diameter of the particle is increased it contributes on the exponent b. The value of 'a' also increases with the increase in diameter because the product of particle diameter, d_p and bed voidage, ε increases. The exponent, b on $(d_p\varepsilon)$ also increases.

From the above discussion the following relation can be drawn:

$$Sh = 0.14\,(d_p\varepsilon)^b\,\varepsilon_i/\varepsilon\,(Re)^c$$

Where

c = 0.8	For 1 mm diameter particle
c = 0.5	For 2 mm diameter particle
c = 0.4	For 3 mm diameter particle

CHAPTER- 5

5. CONCLUSION

Results obtained in the study of effect of fluidization on mass transfer behavior in the electrodeposition on parallel plate electrode, 1 mm, 2 mm and 3 mm grass beads were used as fluidized particles. Four initial bed heights for each particle were used for each bed initial bed height flow rates were varied in the range of 5-8 lit/m to 16.3 lit/m. The following conclusion may be drawn :-

(a) Mass transfer increases with increase in applied voltage till limiting current plateau is reach on the v-1 curve.

(b) In the limiting current region the concentration gradient in the electrolytic cell is constant at the maximum value

(c) The mass transfer rate in a parallel plate electrolytic cell is constant in its mid part.

(d) The mass transfer rate increases with increase in the electrolyte flow rate if the particle size and initial bed height is fixed . But after a certain electrolyte velocity it decreases slightly. So mass transfer rate is maximum for a specific electrolyte flow rate.

(e) For a specific fluidized velocity and for specific fluidized particle the mass transfer rate increases with increase in initial bed height upto a certain limit.

(f) For a specific electrolyte velocity a specific initial bed height the mass transfer rate increases with increase in particle size.

(g) For a specific particle and specific flow rate the mass transfer increases with increase in bed height upto a certain limit.

(h) For a specific particle and specific electrolyte flow rate the mass transfer increases with increase in voidage upto a certain limit and it is highest for a voidage of 0.8.

(i) The Sherwood number increases with increase in Reynolds number for a specific article. The slope of log-log plot of Sh vs. Re is independent of initial bed height. The slope is 0.8 for 1 mm particle and 0.5 and 0.4 for 2 mm and 3 mm dia. The slope decreases with increase in particle size.

(j) The relation between Sherwood Number and Reynolds Number is , as follows:

$Sh = 0.14 (d_p \varepsilon)^b \varepsilon_i/\varepsilon (Re)^c$, c = 0.8 For 1 mm Diameter Particle

$Sh = 0.14 (d_p \varepsilon)^b \varepsilon_i/\varepsilon (Re)^c$, c = 0.5 For 2 mm Diameter Particle

$Sh = 0.14 (d_p \varepsilon)^b \varepsilon_i/\varepsilon (Re)^c$, c = 0.4 For 3 mm Diameter Particle

CHAPTER-6

6. SUGGESTIONS FOR FURTHER WORK:

1. To obtain more accurate result wide range of electrolyte flow rate should be used to observe the profound effect of electrolyte flow on cathode current distribution for the electrolyte flow cells.

2. For electroforming and electroplating, wide range of electrolyte concentration should be used for the observation of the effect of electrolyte concentration on cathodic deposition.

3. To observe the nature and rate of deposition with more accuracy, gradual increase and wide range of current density should be used for electroforming and electroplating.

4. For further work, the effect of distance between the anode and cathode on the rate deposition and the effect of electrolyte pH on cathodic deposition rate as well as the hardness of deposits for copper electroforming should be investigated.

5. Particles of different shape and size should be used to investigate the effect of particle shape and size on the mass transfer coefficient.

6. Cell of different size can be used to investigate for all the above experiments to investigate the effect of cell size on the mass transfer coefficient.

CHAPTER- 7

7. NOMENCLATURE

C_B	Bulk Concentration, gm mole/cm^3
C_S	Surface Concentration, gm mole/cm^3
D	Diffusivity of The Ions, cm^2/s
D_e	Equivalent Diameter
d_p	Particle Diameter
F	Faraday (= 96500 Coulombs)
Fr_{mf}	Froude Number At Minimum Fluidization Velocity
ΔG	Free Energy Change
ΔG^0	Standard Free Energy Change
I	Amount Of Current Passed
i	Current Density, amp/m^2
i_L	Limiting Current Density, amp/m^2
i_o	Exchange Current Density, amp/m^2
J_D	Mass Transfer J-factor
K	Overall Mass Transfer Coefficient, m/sec
K_{lav}	Local Average Mass Transfer Coefficient, m/sec
k_{cav}	Cumulative Average Mass Transfer Coefficient, m/sec
L	Length At The Electrode,
n_a	Activation Overpotential, Volts
n_c	Cumulative Overpotential, Volts
P_r	Prandtl Number
Re	Reynolds Number
Re_i	Modified Reynolds Number
Sc	Schmidt Number

Sh	Sherwood Number
St	Stanton Number
St_1	Modified Stanton Number
T	Absolute Temperature, °K
t	Time of Passage of Current, sec
U	Superficial Elect rolyte Velocity
U_{mf}	Minimum Electrolyte Velocity
v	Voltage Applied Voltage Across The Cell, Volts
v_{min}	Minimum Electrolyzing Voltage
z	Number Of Electrons Involved In The Reaction
ε	Bed Voidage.
μ	Viscosity Of The Solution, cp
ν	Kinematics Viscosity, cm^2/s
δ_n	Thickness Of The Diffusion Layer, cm

CHAPTER- 8

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APPENDIX - A

A. REVIEW OF ELECTROCHEMICAL PRINCIPLES

A.1 INTRODUCTION

A review has been made of relevant literature together with a study of the theoretical principles governing the electrodeposition of copper in the electrodeposition of the copper in the electrochemical reactor. The main aspects that have been considered here are electrode kinetics, mass transfer principles and current distribution in a parallel plate electrochemical reactor.

A.2 BASIC ELECTROCHEMICAL FACTORS

A.2.1 Faraday's Law of Electrolysis

Faraday expressed the two following laws

(1) The amount of electrochemical deposition produced by a current is proportional to the quantity of electricity passing through the electrolytic solution

(2) The amounts of different substances liberated by the same quantity of electricity are proportional to their chemical equivalent weights.

The second law states that the quantity of electricity required one gram equivalent of product should be independent of its nature; this quantity is called Faraday and symbolised as F. Hence the following formula may be drawn

$$\text{i.e., Mole produced } (n) = It/zF \qquad \text{(A.1)}$$

where,

I = the amount of current passed, Ampere

t = the time of passage of current, sec.

z = the number of electrons involved in the reaction

F = the one Faraday (= 96500 Coulombs).

Very often more than one reaction occurs at the electrode. In the deposition of metal, there is evolution of hydrogen or codeposition of another metal with that of desired metal. To achieve a good product purity without any side reaction, the reactor must be operated in a range of electrode potentials which ensures only the desired reaction to take place.

A.2.2 Minimum Electrolysing Voltage

In an electrochemical reactor, electrical energy is supplied to increases the free energy of the reacting species which changes the free energy difference to a negative value and consequently promotes the reaction. The electrical energy is supplied by applying a certain voltage to the reactor. Minimum electrolysing voltage for a given process can be defined as the applied voltage necessary to keep the system at equilibrium when no current flows. The minimum electrolysing voltage, V_{min}, is related to the free energy change for a cell reaction at a certain temperature and pressure under thermodynamic equilibrium and it can be written as,

$$\Delta G = zFV_{min} \tag{A.2}$$

where,

ΔG = the free energy change

z = the number of electrons required for either electrode reactions to produce 1 molecule of product.

F = the Faraday's Constant

The free energy change for an overall reaction

$$aA + bB \rightarrow cC + dD$$

can be written as

$$\Delta G = \Delta G^{o} + RT \ln \frac{a_C^c\, a_D^d}{a_A^a\, a_B^b} \tag{A.3}$$

where, R = the universal gas constant

T = the absolute temperature

ΔG^{o} = the standard free energy change

a, b, c and d are the stoichiometric coefficients of the reactants and the products

a_A, a_B, a_C, a_D are the activities of the species involved.

If all the constituents are at standard states, the minimum electrolysing voltage will be standard minimum electrolysing voltage and it can be written as :

$$\Delta G^{o} = zFV_{min}^{o} \tag{A.4}$$

where V_{min}^{o} is the standard minimum electrolysing voltage corresponding to unit activity of A, B, C, and D.

Combining equations (A.2), (A.3) and (A.4), minimum voltage can be found as,

$$zFV_{min} = zFV_{min}^{o} + RT \ln \frac{a_C^c\, a_D^d}{a_A^a\, a_B^b} \tag{A.5a}$$

$$V_{min} = V_{min}^{o} + \frac{RT}{zF} \ln \frac{a_C^c\, a_D^d}{a_A^a\, a_B^b} \tag{A.5b}$$

This leads to the Nernst equation :

$$V_{min} = V_{min}^{o} - \frac{RT}{zF} \ln \left[\frac{\text{Product of the activities of reduced species}}{\text{Production of the activities of oxidized species}} \right] \tag{A.6}$$

The minimum electrolysing voltage of an electrochemical cell is the difference between the equilibrium or reversible anode (V_a) and cathode (V_c) potentials which can be expressed as :

$$V_{min} = V_a - V_c \tag{A.7}$$

The equilibrium anode and cathode potentials are those electrode potentials which are just sufficient to allow the cathodic deposition and anodic dissolution reactions to proceed at an electrode surface at equal rates so that no net change occurs.

A.2.3 Reactions in Copper Deposition Systems

In the electrorefining processes, the copper deposition takes place in an electrochemical reactor which consists of impure copper anode and a thin sheet of pure copper cathode immersed in an acidified copper sulphate solution. At the soluble anode, metal is oxidized and dissolved as copper ions as follows :

$$Cu \rightarrow Cu^{2+} + 2e \qquad V_a^o = 0.34\,V \tag{A.8}$$

where V_a^o is the standard equilibrium potential for the reaction at the anode when all the species or ions present are at unit activity. As previously stated, the equilibrium potential depends on the activities of the species present in the system, as well as the temperature and pressure, but for a rough estimation the standard equilibrium potentials will be used.

At the cathode the reduction of ion takes place to deposit copper,

$$Cu_u^{2+} + 2e \rightarrow Cu \quad V_C^o = 0.34\,V \tag{A.9}$$

Thus, the theoretical minimum electrolysing voltage for the overall reaction is (0.34 - 0.34) = 0.0 volts.

At high current densities and a sufficiently more negative cathode potential, a secondary reaction occurs, namely hydrogen evolution, as

$$2H^{+}+2e \rightarrow H_2 \qquad V_C^{\circ}=0.0\,V \tag{A.10}$$

The cathode potential should be controlled so that the hydrogen evolution reaction does not occur because it will reduce the current efficiency of copper deposition in the reactor.

A.3 PRACTICAL VOLTAGE REQUIREMENTS

A.3.1 Operating Voltage

In actual operation of an electrochemical reactor, the cell operating voltage is larger than the equilibrium value given by the Nernst equation and can be expressed by considering only one reaction at each electrode as

$$V = V_a - V_c + \sum n_a + \sum n_c + V_s \tag{A.11}$$

where,

- V = cell operating voltage
- Σn_a = combined activation overpotential for both processes
- Σn_c = combined concentration overpotential for both processes
- V_s = potentia l drop across the electrolyte.

An overpotential can be defined as the extra energy necessary to reduce the energy barrier of the rate determining step to a value that enables the electrode reaction to proceed at the desired rate.

A.3.2 Activation Overpotential

Activation overpotential is basically an electrokinetic phenomena and associated with the charge transfer mechanism. It is caused by the irreversibility of the electrode process. The irreversibility of an electrode process increases as the voltage applied to the cell is increased, altering the potential of each electrode.

A theoretical expression can be obtained for the activation overpotential by considering the kinetics of a reversible electrode reaction

$$O + 2e \Leftrightarrow R \tag{A.12}$$

The current density of deposition, i, is related to the overpotential by Arrhenius type rate constant activation energy relationship. Thus an equation for the cathodic current density can be expressed (for small concentration changes between the surface and bulk concentration) as :

$$i = i_o\left[\left\{\exp\frac{-\alpha zF\, n_a}{RT}\right\} - \exp\left\{\frac{(1-\alpha)zF\, n_a}{RT}\right\}\right] \tag{A.13}$$

where, i = cathodic current density

i_o = the exchange current density

α = the fraction of overpotential assisting the discharge process.

For appreciable overpotential, when n_a is greater than 0.05 volts, the second term in equation (A.13) which represents the reaction rate in the reverse direction can be ignored.

Consequently,

$$i = i_o \exp\left\{\frac{-\alpha zF\, n_a}{RT}\right\} \tag{A.14}$$

Rearranging in a more convenient form we have,

$$n_a = \frac{RT}{\alpha zF}\ln i_o - \frac{RT}{\alpha zF}\ln i \tag{A.15a}$$

or, $n_a = a + b \log i$ (A.15b)

where $a = \frac{RT}{\alpha z F} \ln i_o$ and $b = -2.303 \frac{RT}{\alpha z F}$

Equation (A.15) is the "Tafel Equation" which relates overpotential to the net anodic or cathodic current. Tafel equation is most widely used especially for engineering purposes since it has a practical form and it satisfactorily represents the conditions in industrial electrochemical reactors.

A.3.3 Concentration Overpotential

As metal deposition proceeds in the electrochemical reactor, the concentration of the reacting species or ions close to the electrode surface decreases in the absence of adequate supply of ions from the bulk of the solution. This is associated with a rise in electrode potential as given by the Nernst equation (A.6) and is known as concentration overpotential. The movement of ions is controlled by three processes :

(a) Molecular diffusion

(b) Reactant transported by macroscopic hydrodynamic flow known as "convection".

(c) Movement of ions under the influence of an electric field called "ionic migration".

The effect of ionic migration is usually very small in practical electrochemical reactors, including the copper deposition systems. As the solutions contain excess of an indifferent electrolyte normally acid, the hydrogen ion being the main species that carry the electricity through the solution rather than the Cu^{+2} ions. Convection effected by stirring or flow helps to keep a uniform concentration of the electrolyte in the cell as well as near to the electrode wall.

A relationship between current density and the mass transfer coefficient can be written as

$$\frac{i}{zF} = K(C_B - C_S) \qquad \text{(A.16)}$$

where,

K = mass transfer coefficient

C_B = the bulk concentration of solution

C_S = surface concentration.

This expression is an alternative approach to that of Nernst and Merrium's diffusion layer theory for flow systems. The molar flux across the diffusion layer can be expressed by using Fick's law of diffusion as

$$\frac{i}{zF} = \frac{D}{\delta_n}(C_B - C_S) \tag{A.17}$$

where,

D = diffusivity of the ions

δ_n = thickness of the diffusion layer.

Considering Nernst equation (A.6) applied to ionic concentration for a cathodic deposition reaction of the form

$$M^{z+} + ze \rightarrow M \tag{A.18}$$

The value of concentration overpotential is given by

$$n_c = V_C^* - V_C = \frac{RT}{zF} \ln \frac{C_S}{C_B} \tag{A.19}$$

where,

V_C^* = cathode potential during operation

V_C = equilibrium cathode potential

C_S, C_B = surface and bulk concentration of the reacting species.

The simplification made for the derivation of equation (A.19) is based on the consideration of perfectly reversible the processes are irreversible process and it neglects any kinetic effect. In practice most of the processes are irreversible for the deposition of metal or any other reactions to occur.

A.3.4 Concept of Limiting Current Density

As the current in the electrodeposition of a metal increases, the concentration in the vicinity of the cathode decreases until it becomes so small that a substantially constant current density is reached, giving the largest concentration gradient and the highest diffusion rate. This constant current density is referred to as the limiting current density. The limiting current density may also be defined as the maximum operating current that can be generated by a given electrochemical reaction, at a given reactant concentration, under well established hydrodynamic conditions or under steady states.

According to the definition of limiting current, C_S becomes negligibly small so that equation (A.16) becomes

$$\frac{i_L}{zF} = K C_B \qquad \text{(A.20)}$$

where,

i_L = limiting current density.

For a real process C_S is not zero and it has a finite value for an electrochemical reaction to occur, otherwise the concentration overpotential will increase to an infinite value. By eliminating K and zF between equations (A.16) and (A.20) the ratio of concentration becomes

$$i / i_L = \frac{C_B - C_S}{C_B} = 1 - \frac{C_S}{C_B} \qquad \text{(A.21a)}$$

$$\frac{C_S}{C_B} = 1 - \frac{i}{i_L} \tag{A.21b}$$

Combining equations (A.19) and (A.21b) the value of concentration overpotential is given by

$$n_c = \frac{RT}{zF} \ln\left(1 - \frac{i}{i_L}\right) \tag{A.22}$$

The effect of concentration overpotential in an electrochemical reactor can be reduced by increasing the mass transfer rate (i.e., decreasing the thickness of diffusion layer), resulting in an increase in the limiting current. The mass transfer co-efficient depends on the shape and entrance condition of the cell, the electrolyte and the reaction taking place. The limiting current can be increased by increasing the temperature of the electrolyte causing an increase in diffusivities.

Figure 2.1 shows a typical polarization curve characterized by the occurrence of a limiting current plateau and this is terminated by the onset of a secondary reaction, usually a gas evaluation.

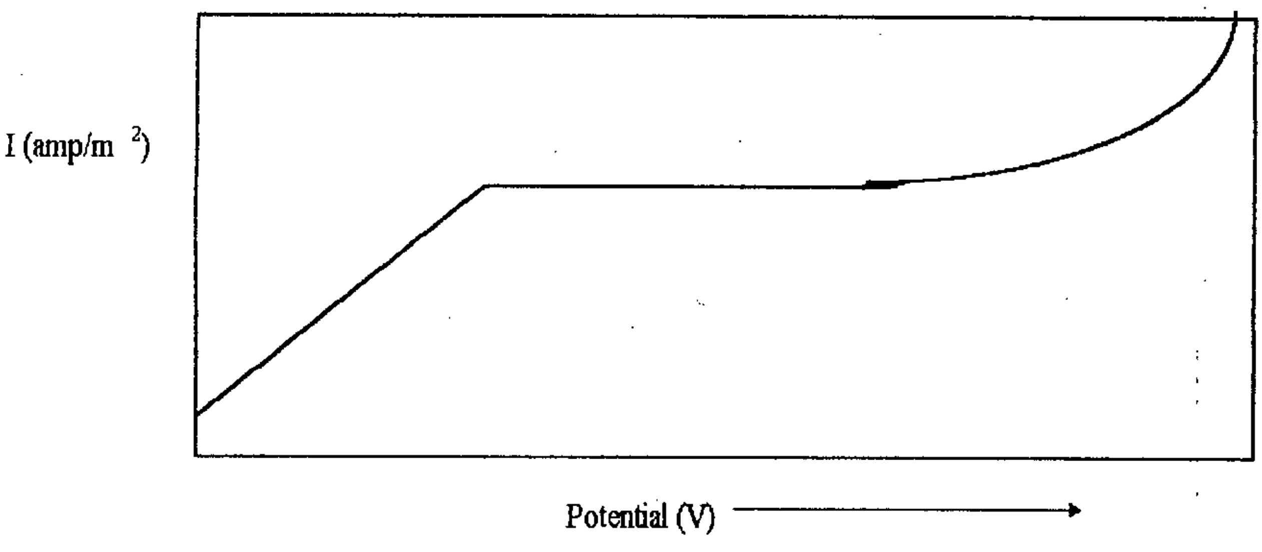

Fig. A.1 : Typical Polarization curve.

For the systems where secondary reaction affects the operation of the reactor, most of the reactors are operated below the limiting current. Practical operation of electrochemical reactors are carried out well below the limiting current, because the application of increased voltage at this stage does not improve the reaction rate and decreases the current efficiency. Nevertheless, limiting current measurements provide a very convenient technique for mass transfer studies because mass transfer coefficients (K) can be readily and accurately calculated from the experimentally obtained current plateau on a current density - potential plot as shown in Figure 2.1.

A.3.5 Potential Drop in Solution

This added energy is caused by a change in solution conductivity and by the formation of poorly conducting films on electrodes. This has also been designated as 'IR' drop. The conductivity of an electrolyte can be related to the solution voltage drop by the following equation

$$V_S = \frac{iS}{k} \tag{A.23}$$

where,

S = distance between the electrode, m.

k = electrolyte conductivity, mho/m.

The conductivity of the solution can be increased by the addition of excess indifferent electrolyte which is normally acid or alkali and the presence of indifferent electrolyte reduces the migration flux of the reacting species.

A.4 Current Distribution in an Electrochemical Reactor

A desirable electrochemical reactor is one in which the current is uniformly distributed. Irregularities from the average current densities and uneven potential distribution can lead to a loss in product selectivity and local corrosion problems. For a parallel plate reactor, having an electrode of equal area on the entire opposite side of the reactor one would expect uniform current distribution due to symmetry. When the electrodes are polarized, the current distribution in a reactor not only depends on the geometry of the reactor and electrodes but also on the reaction occurring at the electrode surface, the electrolyte composition, the effect of ionic migration and concentration gradient and voltage drop within an electrode. These effects are very important for systems where reactions are slow, reactions occur in a narrow potential range, electrolyte conductivity is low and where the cell is operating much below the limiting current.

APPENDIX - B1

CELL DIMENSIONS, PHYSICAL PROPERTIES OF COPPER SULPHATE IN SULPHURIC ACID SOLUTION AND OTHER RELEVANT DATA OF FLUIDIZED BED

The physical properties of 0.015 M Copper sulphate solution in 1.5 sulphuric acid has been taken from Stanmore and Wilson. They collected the data from several sources. For dilute solutions, the diffusivity of the copper ion can be taken equal to that of copper sulphate without any appreciable error.

TABLE B.1

Solution Characteristics for 0.015 M $CuSO_4$ in 1.5 M H_2SO_4

Temperature (°C)	Diffusivity $D(cm^2/sec) \times 10^6$	Kinematics Viscosity cm^2/sec	Schmidt No. Sc = υ/D.
21.5	6.15	1.035	1682.9
30.0	7.89	0.889	1126.9
40.0	9.50	0.718	754.0

The Cell Dimensions

Length of electrode (L)	= 0.3 m
Width of the electrodes (W)	= 0.2 m.
Spacing between the electrodes (S)	= 0.02 m
Equivalent diameter (D_e)	= 0.03636 m
Aspect ratio (s/w)	= 0.1

Total Electrode area (L*w) = 0.06 m^2

Cross sectional area for flow (L*w) = 0.004 m^2

<u>The Data for the Fluidized Bed</u>

Average diameters of the glass particles = 1.0 mm, 2.0 mm and 3.0 mm. Density of the glass particles = 2550 Kg/m^3

TABLE B.2

Static bed Voidage and Froude number for the glass particle.

Particle size, mm	Density ρ_S, Kg/m^3	Static bed Voidages (ε_0)	Froude number (U^2_{mf}/gd_p)
1	-	0.375	0.18
2	2550	0.40	0.25
3	-	0.42	0.33

Minimum fluidization velocity, U_{mf} has been calculated theoretically.

APPENDIX - C

LOCAL CURRENT OF INDIVIDUAL SECTION FOR INCREASING APPLIED VOLTAGE

Table C1: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) **Initial Bed Height = 6.0 cm** **Flowrate = 5.8 Lit/min**

Temperature = 29 C **Voidage = 0.9**

SECTION ↓	VOLTAGE (m V) →										
	50	100	150	200	250	300	350	400	450	500	550
1	4.34	6.65	8.2	10.1	12	13.6	13.9	14.2	21.7	28.2	32.9
2	3.58	5.7	8	9	11.2	13.5	13.9	14	20.5	28	32.7
3	3.58	5.1	7.5	8.5	11	12	12.8	12.8	19.4	26	30.7
4	3.34	5.5	7.5	8.5	10.2	11	11.9	11.9	19.4	25.7	30.4
5	3.34	5.5	7.5	8.5	10.2	11	12	12	19.4	25.7	30.4
6	11.51	17.2	20.45	22.8	23	23.8	24.2	25.7	39	50.2	69.1
7	10.43	15.7	20.41	22.8	23	22.5	23	23	37.4	48	66.9
8	9.75	15.2	19.86	19.5	20.5	19.8	20.1	22.6	36.4	46.6	65.5
9	9.31	14.2	18.9	18.5	19.9	19.7	20.5	21.7	36.4	46.6	65.5
10	8.04	13.5	18.7	16.5	16	15.7	17.7	18.5	37.5	35.8	54.7
11	3.22	5.6	6.2	10.5	8.6	9.3	9.8	9.8	15.2	20.3	25.5
12	3.04	5.4	6	7.6	8.3	9.3	9.8	9.8	15.2	20.3	25
13	3.04	5.4	6	7.4	8.4	9.5	9.5	9.5	15.4	20.7	24.4
14	3.24	5.6	6.2	7.8	8.6	9.3	9.5	9.5	16.5	20.6	25.5
15	4.24	6.5	7.8	8.8	9.3	11	11.5	12	17.4	21	26.8
Total	84	133	169.2	186.8	200.2	211	220.1	227	367	463.7	606

Table C2: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) **Initial Bed Height = 6.0 cm** **Flowrate = 7.9 Lit/ min**

Temperature = 29 C **Voidage = 0.9**

← V O L T A G E →
(m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	4.51	7.04	8.56	10.7	12.66	14.23	14.66	18.2	26.8	33.1	35.95
2	3.75	6.09	8.36	9.6	11.86	14.13	14.66	18	25.6	32.9	35.75
3	3.75	5.49	7.86	9.1	11.66	12.63	13.56	16.8	24.5	30.9	33.75
4	3.51	5.89	7.86	9.1	10.86	11.63	12.66	15.9	24.5	30.6	33.45
5	3.51	5.89	7.86	9.1	10.86	11.63	12.76	16	24.5	30.6	33.45
6	12.19	18.78	21.92	25.2	25.64	26.32	27.24	41.7	59.4	69.8	81.3
7	11.11	17.51	21.88	25.2	25.64	25.02	26.04	39	57.8	67.6	79.1
8	10.43	16.77	21.33	21.9	23.14	22.32	23.14	38.6	56.8	66.2	77.7
9	9.99	15.78	20.37	20.9	22.54	22.22	23.54	37.7	56.8	66.2	77.7
10	8.72	15.07	20.17	18.9	18.64	18.22	20.74	34.5	57.9	55.4	66.9
11	3.39	5.99	6.56	11.1	9.26	9.93	10.56	13.8	20.3	25.1	28.55
12	3.21	5.79	6.36	8.2	8.96	9.93	10.66	13.8	20.3	25.1	28.05
13	3.21	5.79	6.36	8	9.06	10.13	10.26	13.5	20.5	25.5	27.45
14	3.39	5.99	6.55	8.4	9.26	9.93	10.26	13.5	21.6	25.7	28.55
15	4.5	6.89	8	9.6	9.96	11.73	12.36	16	22.7	25.8	29.85
Total	89.17	144.8	180	205	220	230	243	347	520	610.5	697.5

Table C3: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) Initial Bed Height = 6.0 cm Flowrate = 8.9 Lit/ min

Temperature = 29 C Voidage = 0.9

	VOLTAGE (m V) →										
CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	4.34	7.38	9.23	11.8	13.89	15.23	15.36	20.5	29.9	35.8	38.72
2	3.58	6.43	9.03	10.7	13.09	15.13	15.36	20.3	28.7	35.6	38.52
3	3.58	5.83	8.53	10.2	12.89	13.63	14.26	19.1	27.6	33.6	36.52
4	3.34	6.23	8.53	10.2	12.09	12.63	13.36	18.2	27.6	33.3	36.22
5	3.34	6.23	8.53	10.2	12.09	12.63	13.46	18.3	27.6	33.3	36.22
6	11.51	20.13	24.57	29.6	30.56	30.32	30.04	50.9	71.8	80.6	92.4
7	10.43	18.66	24.53	29.6	30.56	29.02	28.84	48.2	70.2	78.4	90.2
8	9.75	18.12	23.98	26.3	28.06	26.32	25.94	47.8	69.2	77	88.8
9	9.31	17.13	23.02	25.3	27.46	26.22	26.34	46.9	69.2	77	88.8
10	8.04	16.42	22.82	23.3	23.56	22.22	23.54	43.7	70.3	66.2	78
11	3.22	6.33	7.23	12.2	10.49	10.93	11.26	16.1	23.4	27.9	31.32
12	3.04	6.13	7.03	9.3	10.19	10.93	11.26	16.1	23.4	27.9	30.82
13	3.04	6.13	7.03	9.1	10.29	11.13	10.96	15.8	23.6	28.3	30.22
14	3.24	6.63	7.11	9.7	10.49	11.03	11.06	15.8	24.7	28.2	31.32
15	4.24	7.23	8.83	10.5	11.29	12.63	12.96	18.3	25.8	28.9	32.42
Total	84	155	200	238	257	260	264	416	613	692	780.5

Table C4: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) **Initial Bed Height = 6.0 cm** **Flowrate = 10.5 Lit/ min**

Temperature = 29 C **Voidage = 0.9**

CATHODE SECTION	VOLTAGE (m V) → 50	100	150	200	250	300	350	400	450	500	550
1	5.91	8.78	10.6	12.9	15.16	16.73	20.16	23.1	33.37	44.07	51.47
2	5.15	7.83	10.4	11.8	14.36	16.63	20.16	22.9	32.17	43.87	51.27
3	5.15	7.23	9.9	11.3	14.16	15.13	19.06	21.7	31.07	41.87	49.27
4	4.91	7.63	9.9	11.3	13.36	14.13	18.16	20.8	31.07	41.57	48.97
5	4.91	7.63	9.9	11.3	13.36	14.13	18.26	20.9	31.07	41.57	48.97
6	17.79	25.73	30.05	34	35.64	36.3	49.24	61.3	85.68	113.84	143.38
7	16.71	24.26	30.01	34	35.64	35	48.04	58.6	84.08	111.64	141.18
8	16.03	23.72	29.46	30.7	33.14	32.3	45.14	58.2	83.08	110.24	139.78
9	15.59	22.73	28.5	29.7	32.54	32.2	45.54	57.3	83.08	110.24	139.78
10	14.32	22.02	28.3	27.7	28.64	28.2	42.74	54.1	84.18	99.44	128.98
11	4.79	7.73	8.6	13.3	11.76	12.43	16.06	18.7	26.87	36.17	44.07
12	4.61	7.53	8.4	10.4	11.46	12.43	16.06	18.7	26.87	36.17	43.57
13	4.61	7.53	8.4	10.2	11.56	12.63	15.76	18.4	27.07	36.17	42.97
14	4.81	7.73	8.6	10.4	11.76	12.43	15.86	18.4	28.17	36.47	44.07
15	5.81	8.93	9.98	11	12.46	14.33	17.76	20.9	29.17	36.67	45.27
Total	131.1	197	241	270	295	305	408	494	717	940	1163

Table C5: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) Initial Bed Height = 6.0 cm Flowrate = 11.4 Lit/ min

Temperature = 29 C Voidage = 0.9

		VOLTAGE (m V)										
		50	100	150	200	250	300	350	400	450	500	550
CATHODE SECTION	1	6.22	9.78	11.9	14.54	16.62	17.57	18.44	23.1	33.37	44.07	51.47
	2	5.26	8.83	11.7	13.44	15.62	17.47	18.44	22.9	32.17	43.87	51.27
	3	5.26	8.23	11.2	12.94	15.42	15.97	17.34	21.7	31.07	41.87	49.27
	4	5.02	8.63	11.2	12.94	14.62	14.97	16.44	20.8	31.07	41.57	48.97
	5	5.02	8.63	11.2	12.94	14.62	14.97	16.54	20.9	31.07	41.57	48.97
	6	18.23	29.73	35.25	40.56	40.68	39.7	42.33	61.3	85.7	113.68	143.38
	7	17.15	28.26	35.21	40.56	40.68	38.4	41.13	58.6	84.1	111.48	141.18
	8	16.47	27.72	34.64	37.26	38.18	35.7	38.23	58.2	83.1	110.08	139.78
	9	16.03	26.73	33.7	36.25	36.36	35.6	38.63	57.3	83.1	110.08	139.78
	10	14.76	26.02	33.5	34.26	33.68	31.6	35.83	54.1	84.2	99.28	128.98
	11	4.9	8.73	9.9	14.94	13.02	13.27	14.34	18.7	26.87	36.17	44.07
	12	4.72	8.53	9.7	12.04	12.72	13.27	14.34	18.7	26.87	36.17	43.57
	13	4.72	8.53	9.7	11.84	11.84	13.47	14.04	18.4	27.07	36.57	42.97
	14	4.94	9.03	9.9	12.24	12.26	13.27	14.04	18.4	28.17	36.67	44.07
	15	5.84	9.63	11.3	13.24	13.69	14.97	19.2	20.9	29.07	36.87	45.27
Total		134.54	227	280	320	330	330.2	359.31	494	717	940	1163

Table C6: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) | Initial Bed Height = 6.0 cm | Flowrate = 12.7 Lit/ min

Temperature = 29 C | Voidage = 0.5

← V O L T A G E →
(m V)

		50	100	150	200	250	300	350	400	450	500	550
CATHODE SECTION ↓	1	6.58	10.55	13.23	16.5	18.06	22.56	28.73	30.63	35.13	47.4	56.03
	2	5.82	9.6	13.03	15.4	17.26	22.46	28.73	30.43	33.93	47.2	55.83
	3	5.82	9	12.53	14.9	17.06	20.96	27.63	29.23	32.83	45.2	53.83
	4	5.58	9.4	12.53	14.9	16.26	19.96	26.73	28.33	32.83	44.9	53.53
	5	5.58	9.4	12.53	14.9	16.26	19.96	26.83	28.43	32.83	44.9	53.53
	6	20.47	32.81	40.57	48.4	47.24	59.64	83.52	91.42	92.72	127	161.62
	7	19.39	31.34	40.53	48.4	47.24	58.34	82.32	88.72	91.12	124.8	159.42
	8	18.71	30.8	39.98	45.1	44.74	55.64	79.42	88.32	90.12	123.4	158.02
	9	18.27	29.81	39.02	44.1	44.14	55.54	79.82	87.42	90.12	123.4	158.02
	10	17	29.1	38.82	42.1	40.24	51.54	77.02	84.22	91.22	112.6	147.22
	11	5.46	9.5	11.23	16.9	14.66	18.26	24.63	26.23	28.63	39.5	48.63
	12	5.28	9.3	11.03	14	14.36	18.26	24.63	26.23	28.63	39.5	48.13
	13	5.28	9.3	11.03	13.8	14.46	18.46	24.33	25.93	28.83	39.9	47.53
	14	5.48	9.5	11.23	14.2	14.66	18.26	24.33	25.93	29.93	39.8	48.63
	15	6.48	10.4	12.83	15.2	15.36	19.96	26.33	28.43	30.83	40.2	49.93
Total		151.2	249.8	320.12	378.8	382	479.8	665	719.9	769.7	1039.7	1299.9

Table C7: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) Initial Bed Height = 6.0 cm Flowrate = 14.6 Lit/ min

Temperature = 29 C Voidage = 0.9

← V O L T A G E → (m V)

CATHODE SECTION	50	100	150	200	250	300	350	400	450	500	550
1	7.14	12.42	16.5	18.63	23.16	27.7	33.66	39.27	48.47	61.4	75.7
2	6.38	11.47	16.3	17.53	22.36	27.6	33.56	39.07	47.27	61.2	75.5
3	6.38	10.87	15.8	17.03	22.16	26.1	32.46	37.87	46.17	59.2	73.5
4	6.14	11.27	15.8	17.03	21.36	25.1	31.56	36.97	46.17	58.9	73.2
5	6.14	11.27	15.8	17.03	21.36	25.1	31.66	37.07	46.17	58.9	73.2
6	22.71	40.29	53.65	56.92	67.64	80.2	102.84	126	146.1	183	240.3
7	21.63	38.82	53.61	56.92	67.64	78.5	101.64	123.3	144.5	180.8	238.1
8	20.95	38.28	53.06	53.62	65.14	76.2	98.74	122.9	143.5	179.4	236.7
9	20.51	37.29	52.1	52.62	64.54	76.1	99.14	122	143.5	179.4	236.7
10	19.24	36.58	51.9	50.62	60.64	72.1	96.34	118.8	144.6	168.6	225.9
11	6.02	11.37	14.5	19.03	19.75	23.4	29.46	34.87	41.97	53.5	68.3
12	5.84	11.17	14.3	16.13	19.46	23.4	29.46	34.87	41.97	53.5	67.8
13	5.84	11.17	14.3	15.93	19.56	23.9	29.16	34.57	42.17	53.9	67.2
14	6.04	11.37	14.5	16.33	19.76	23.4	29.16	34.57	43.27	53.8	68.3
15	7.04	12.27	16.1	17.33	20.46	25.1	31.16	37.07	44.17	54.2	69.6
Total	168	305.9	418.22	442.7	535	634	809.9	979.1	1170	1459.7	1890

Table C8: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) Initial Bed Height = 9.0 cm Flowrate = 5.8 Lit/ min

Temperature = 29 C Voidage = 0.85

CATHODE SECTION ↓	VOLTAGE (m V) →										
	50	100	150	200	250	300	350	400	450	500	550
1	6.54	11.55	14.13	17.07	21.63	25.97	30.06	36.17	38.17	50.4	61.7
2	5.78	10.6	13.93	15.97	20.83	25.87	30.06	35.97	36.97	50.2	61.5
3	5.78	10	13.43	15.47	20.63	24.37	28.96	34.77	35.87	48.2	59.5
4	5.54	10.4	13.43	15.47	19.83	23.37	28.06	33.87	35.87	47.9	59.2
5	5.54	10.4	13.43	15.47	19.83	23.37	28.16	33.97	35.87	47.9	59.2
6	20.31	36.81	44.17	50.68	61.52	73.28	88.84	113.6	104.9	139	184.3
7	19.23	35.34	44.13	50.68	61.52	71.98	87.64	110.9	103.3	136.8	182.1
8	18.55	34.8	43.58	47.38	59.02	69.28	84.74	110.5	102.3	135.4	180.7
9	18.11	33.81	42.62	46.38	58.42	69.18	85.14	109.6	102.3	135.4	180.7
10	16.84	33.1	42.42	44.38	54.52	65.18	82.34	106.4	103.4	124.6	169.9
11	5.42	10.5	12.13	17.47	18.23	21.67	25.96	31.77	31.67	42.5	54.3
12	5.24	10.3	11.93	14.57	17.93	21.67	25.96	31.77	31.67	42.5	53.8
13	5.24	10.3	11.93	14.37	18.03	21.87	25.66	31.47	31.87	42.9	53.2
14	5.44	10.5	12.13	14.77	18.23	21.67	25.66	31.47	32.97	42.8	54.3
15	6.44	11.4	13.73	15.77	18.93	23.37	27.66	33.97	33.87	43.2	55.6
Total	150	279.8	347.12	395.9	489.1	582.1	704.9	886.1	860.9	1129.7	1470

Table C9: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) Initial Bed Height = 9.0 cm Flowrate = 7.9 Lit/ min

Temperature = 29 C Voidage = 0.85

Cathode Section	VOLTAGE (m V) → 50	100	150	200	250	300	350	400	450	500	550
1	6.71	9.24	10.76	12.9	14.86	16.43	16.86	20.4	29	35.3	38.15
2	5.95	8.29	10.56	11.8	14.06	16.33	16.86	20.2	27.8	35.1	37.95
3	5.95	7.69	10.06	11.3	13.86	14.83	15.76	19	26.7	33.1	35.95
4	5.71	8.09	10.06	11.3	13.06	13.83	14.86	18.1	26.7	32.8	35.65
5	5.71	8.09	10.06	11.3	13.06	13.83	14.96	18.2	26.7	32.8	35.65
6	15.39	21.98	25.12	28.4	28.84	29.52	30.44	44.9	62.6	73	84.5
7	14.31	20.71	25.08	28.4	28.84	28.22	29.24	42.2	61	70.8	82.3
8	13.63	19.97	24.53	25.1	26.34	25.52	26.34	41.8	60	69.4	80.9
9	11.29	17.08	21.67	22.2	23.84	23.52	24.84	39	58.1	67.5	79
10	10.02	16.37	21.47	20.2	19.94	19.52	22.04	35.8	59.2	56.7	68.2
11	4.39	6.99	7.56	12.1	10.26	10.93	11.56	14.8	21.3	26.1	29.55
12	4.21	6.79	7.36	9.2	9.96	10.93	11.56	14.8	21.3	26.1	29.05
13	4.21	6.79	7.36	9	10.06	11.13	11.26	14.5	21.5	26.5	28.45
14	4.39	6.99	7.55	9.4	10.26	10.93	11.26	14.5	22.6	26.7	29.55
15	5.5	7.89	9	10.6	10.96	12.73	13.36	17	23.7	26.8	30.85
Total	117.37	173	208.2	233.2	248.2	258.2	271.2	375.2	548.2	638.7	725.7

Table C10: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) Initial Bed Height = 9.0 cm Flowrate = 8.9 Lit/ min

Temperature = 29 C Voidage = 0.61

← V O L T A G E → (m V)

Cathode Section	50	100	150	200	250	300	350	400	450	500	550
1	6.24	9.28	11.13	13.7	15.79	17.13	17.26	22.4	31.8	37.7	40.62
2	5.48	8.33	10.93	12.6	14.99	17.03	17.26	22.2	30.6	37.5	40.42
3	5.48	7.73	10.43	12.1	14.79	15.53	16.16	21	29.5	35.5	38.42
4	5.24	8.13	10.43	12.1	13.99	14.53	15.26	20.1	29.5	35.2	38.12
5	5.24	8.13	10.43	12.1	13.99	14.53	15.36	20.2	29.5	35.2	38.12
6	18.91	27.53	31.97	37	37.96	37.72	37.44	58.3	79.2	88	99.8
7	17.83	26.06	31.93	37	37.96	36.42	36.24	55.6	77.6	85.8	97.6
8	17.15	25.52	31.38	33.7	35.46	33.72	33.34	55.2	76.6	84.4	96.2
9	16.71	24.53	30.42	32.7	34.86	33.62	33.74	54.3	76.6	84.4	96.2
10	17.4	15.44	30.22	30.7	30.96	29.62	30.94	51.1	77.7	73.6	85.4
11	5.32	7.59	8.16	12.7	10.86	14.53	15.16	18.4	24.9	29.7	30.7
12	4.81	7.39	7.96	9.8	10.56	11.53	12.16	15.4	21.9	26.7	29.65
13	4.81	7.39	7.96	9.6	10.66	11.73	11.86	15.1	22.1	27.1	29.05
14	4.99	7.59	8.15	10	10.86	11.53	11.86	15.1	23.2	27.3	30.15
15	6.1	8.49	9.6	11.2	11.56	13.33	13.96	17.6	24.3	27.4	31.45
Total	141.71	199.1	251.1	287	305.25	312.5	318	462	655	735.5	821.9

Table C11: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) Initial Bed Height = 9.0 cm Flowrate= 10.5 Lit/ min

Temperature = 29 C Voidage = 0.85

Cathode Section	Voltage (mV) → 50	100	150	200	250	300	350	400	450	500	550
1	8.11	10.98	12.8	15.1	17.36	18.93	22.36	25.3	35.57	46.27	53.67
2	7.35	10.03	12.6	14	16.56	18.83	22.36	25.1	34.37	46.07	53.47
3	7.35	9.43	12.1	13.5	16.36	17.33	21.26	23.9	33.27	44.07	51.47
4	7.11	9.83	12.1	13.5	15.56	16.33	20.36	23	33.27	43.77	51.17
5	7.11	9.83	12.1	13.5	15.56	16.33	20.46	23.1	33.27	43.77	51.17
6	26.19	34.13	38.45	42.4	44.04	44.7	57.64	69.7	94.08	122.24	151.78
7	25.11	32.66	38.41	42.4	44.04	43.4	56.44	67	92.48	120.04	149.58
8	24.43	32.12	37.86	39.1	41.54	40.7	53.54	66.6	91.48	118.64	148.18
9	23.99	31.13	36.9	38.1	40.94	40.6	53.94	65.7	91.48	118.64	148.18
10	22.72	30.42	36.7	36.1	37.04	36.6	51.14	62.5	92.58	107.84	137.38
11	6.39	9.33	10.2	14.9	13.36	14.03	17.66	20.3	28.47	37.77	45.67
12	6.21	9.13	10	12	13.06	14.03	17.66	20.3	28.47	37.77	45.17
13	6.21	9.13	10	11.8	13.16	14.23	17.36	20	28.67	37.77	44.57
14	6.41	9.33	10.2	12	13.36	14.03	17.46	20	29.77	38.07	45.67
15	9.01	12.13	13.18	14.2	15.66	17.53	20.96	24.1	32.37	39.87	48.47
Total	193.7	259.6	303.6	332.6	357.6	367.6	470.6	556.6	779.6	1002.6	1225.6

Table C12: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) Initial Bed Height = 9.0 cm Flowrate =11.4 Lit/ min

Temperature = 29 C Voidage = 0.85

CATHODE SECTION ↓	VOLTAGE (m V) → 50	100	150	200	250	300	350	400	450	500	550
1	8.82	12.38	14.5	17.14	19.22	20.17	21.04	25.7	35.97	46.67	54.07
2	7.86	11.43	14.3	16.04	18.22	20.07	21.04	25.5	34.77	46.47	53.87
3	7.86	10.83	13.8	15.54	18.02	18.57	19.94	24.3	33.67	44.47	51.87
4	7.62	11.23	13.8	15.54	17.22	17.57	19.04	23.4	33.67	44.17	51.57
5	7.62	11.23	13.8	15.54	17.22	17.57	19.14	23.5	33.67	44.17	51.57
6	26.23	37.73	43.25	48.56	48.68	47.7	50.33	69.3	93.7	121.68	151.38
7	25.15	36.26	43.21	48.56	48.68	46.4	49.13	66.6	92.1	119.48	149.18
8	24.47	35.72	42.64	45.26	46.18	43.7	46.23	66.2	91.1	118.08	147.78
9	24.03	34.73	41.7	44.26	44.36	43.6	46.63	65.3	91.1	118.08	147.78
10	22.76	34.02	41.5	42.26	41.68	39.6	43.83	62.1	92.2	107.28	136.98
11	6.7	10.53	11.7	16.74	14.82	15.07	16.14	20.5	28.67	37.97	45.87
12	6.52	10.33	11.5	13.84	14.52	15.07	16.14	20.5	28.67	37.97	45.37
13	6.52	10.33	11.5	13.64	13.64	15.27	15.84	20.2	28.97	38.37	44.77
14	6.74	10.83	11.7	14.04	14.05	15.07	15.84	20.2	29.97	38.47	45.87
15	7.64	11.43	13.1	15.04	15.49	16.77	21	22.7	30.87	38.67	47.07
Total	196.54	289	342	382	392	392.2	421.31	556	779	1002	1225

Table C13: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) Initial Bed Height = 9.0 cm Flowrate = 12.7 Lit/ min

Temperature = 29 C Voidage = 0.85

VOLTAGE (m V)

CATHODE SECTION	50	100	150	200	250	300	350	400	450	500	550
1	9.18	13.15	15.83	19.1	20.66	25.16	31.33	33.23	37.73	50	58.63
2	8.42	12.2	15.63	18	19.86	25.06	31.33	33.03	36.53	49.8	58.43
3	8.42	11.6	15.13	17.5	15.66	23.56	30.23	31.83	35.43	47.8	56.43
4	8.18	12	15.13	17.5	18.86	22.56	29.33	30.93	35.43	47.5	56.13
5	8.18	12	15.13	17.5	18.86	22.56	29.43	31.03	35.43	47.5	56.13
6	29.07	41.41	49.17	57	55.84	68.24	92.12	100	101.3	135.6	170.22
7	27.99	39.94	49.13	57	55.84	66.94	90.92	97.32	99.72	133.4	168.02
8	27.31	39.4	48.58	53.7	53.34	64.24	88.02	96.92	98.72	132	166.62
9	26.87	38.41	47.62	52.7	52.74	64.14	88.42	96.02	98.72	132	166.62
10	25.6	37.7	47.42	50.7	48.84	60.14	85.62	92.82	99.82	121.2	155.82
11	7.56	11.6	13.33	19	16.76	20.36	26.73	28.33	30.73	41.6	50.73
12	7.38	11.4	13.13	16.1	16.46	20.36	26.73	28.33	30.73	41.6	50.23
13	7.38	11.4	13.13	15.9	16.56	20.56	26.43	28.03	30.93	42	49.63
14	7.58	11.6	13.33	16.3	16.76	20.36	26.43	28.03	32.03	41.9	50.73
15	8.58	12.5	14.93	17.3	17.46	22.06	28.43	30.53	32.93	42.3	52.03
Total	217.7	316.3	386.62	445.3	448.5	546.3	731.5	786.4	836.2	1106.2	1366.4

Table C14: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) Initial Bed Height = 9.0 cm Flowrate = 14.7 Lit/ min

Temperature = 29 C Voidage = 0.85

← V O L T A G E →
(m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	9.44	14.72	18.8	20.93	25.46	30	35.86	41.57	50.77	63.7	78
2	8.68	13.77	18.6	19.83	24.66	29.9	35.86	41.37	49.57	63.5	77.8
3	8.68	13.17	18.1	19.33	24.46	28.4	34.76	40.17	48.47	61.5	75.8
4	8.44	13.57	18.1	19.33	23.66	27.4	33.86	39.27	48.47	61.2	75.5
5	8.44	13.57	18.1	19.33	23.66	27.4	33.96	39.37	48.47	61.2	75.5
6	28.81	46.39	59.75	63.02	73.74	86.3	108.94	132.1	152.2	189.1	246.4
7	27.73	44.92	59.71	63.02	73.74	85	107.74	129.4	150.6	186.9	244.2
8	27.05	44.38	59.16	59.72	71.24	82.3	104.84	129	149.6	185.5	242.8
9	26.61	43.39	58.2	58.72	70.64	82.2	105.24	128.1	149.6	185.5	242.8
10	25.34	42.68	58	56.72	66.74	78.2	102.44	124.9	150.7	174.7	232
11	7.92	13.27	16.4	20.93	21.66	25.3	31.36	36.77	43.87	55.4	70.2
12	7.74	13.07	16.2	18.03	21.36	25.3	31.36	36.77	43.87	55.4	69.7
13	7.74	13.07	16.2	17.83	21.46	25.5	31.06	36.47	44.07	55.8	69.1
14	7.94	13.27	16.4	18.23	21.66	25.3	31.06	36.47	45.17	55.7	70.2
15	8.94	14.17	18	19.23	22.36	27	33.06	38.97	46.07	56.1	71.5
Total	219.5	357.4	469.72	494.2	586.5	685.5	861.4	1031	1222	1511.2	1941.5

Table C15: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) Initial Bed Height = 12.0 cm Flowrate = 5.8 Lit/ min

Temperature = 29 C Voidage = 0.8

← V O L T A G E →
(m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	9.14	14.15	16.73	19.67	24.23	28.57	32.66	38.77	40.77	53	64.3
2	9.14	13.2	16.53	18.57	23.43	28.47	32.66	38.57	39.57	52.8	64.1
3	8.38	12.6	16.03	18.07	23.23	26.97	31.56	37.37	38.47	50.8	62.1
4	8.14	13	16.03	18.07	22.43	25.97	30.66	36.47	38.47	50.5	61.8
5	8.14	13	16.03	18.07	22.43	25.97	30.76	36.57	38.47	50.5	61.8
6	27.41	43.91	51.27	57.78	68.62	80.38	95.94	120.7	112	146.1	191.4
7	26.33	42.44	51.23	57.78	68.62	79.08	94.74	118	110.4	143.9	189.2
8	25.65	41.9	50.68	54.48	66.12	76.38	91.84	117.6	109.4	142.5	187.8
9	25.21	40.91	49.72	53.48	65.52	76.28	92.24	116.7	109.4	142.5	187.8
10	22.04	38.3	47.62	49.58	59.72	70.38	87.54	111.6	108.6	129.8	175.1
11	7.52	12.6	14.23	19.57	20.33	23.77	28.06	33.87	33.77	44.6	56.4
12	7.34	12.4	14.03	16.67	20.03	23.77	28.06	33.87	33.77	44.6	55.9
13	:7.34	12.4	14.03	16.47	20.13	23.97	27.76	33.57	33.97	45	55.3
14	7.54	12.6	14.23	16.87	20.33	23.77	27.76	33.57	35.07	44.9	56.4
15	8.54	13.5	15.83	17.87	21.03	25.47	29.76	36.07	35.97	45.3	57.7
Total	207.86	336.9	404.22	453	546.2	639.2	762	943.2	918	1186.8	1527.1

Table C16: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) Initial Bed Height = 12.0 cm Flowrate = 7.9 Lit/ min

Temperature = 29 C Voidage = 0.8

← V O L T A G E →
(m V)

CATHODE SECTION ↓											
1	9.41	11.94	13.46	15.6	17.56	19.13	19.56	23.1	31.7	38	40.85
2	8.65	10.99	13.26	14.5	16.76	19.03	19.56	22.9	30.5	37.8	40.65
3	8.65	10.39	12.76	14	16.56	17.53	18.46	21.7	29.4	35.8	38.65
4	8.41	10.79	12.76	14	15.76	16.53	17.56	20.8	29.4	35.5	38.35
5	8.41	10.79	12.76	14	15.76	16.53	17.66	20.9	29.4	35.5	38.35
6	22.79	29.38	32.52	35.8	36.24	36.92	37.84	52.3	70	75.7	87.2
7	21.71	28.11	32.48	35.8	36.24	35.62	36.64	49.6	68.4	73.5	85
8	21.03	27.37	31.93	32.5	33.74	32.92	33.74	49.2	67.4	72.1	83.6
9	18.69	24.48	29.07	29.6	31.24	30.92	32.24	46.4	65.5	70.2	81.7
10	15.32	21.67	26.77	25.5	25.24	24.82	27.34	41.1	64.5	59.4	70.9
11	7.09	9.69	10.26	14.8	12.96	13.63	14.26	17.5	24	28.8	32.25
12	6.91	9.49	10.06	11.9	12.66	13.63	14.26	17.5	24	28.8	31.75
13	6.91	9.49	10.06	11.7	12.76	13.83	13.96	17.2	24.2	29.2	31:15
14	7.09	9.69	10.25	12.1	12.96	13.63	13.96	17.2	25.3	29.4	32.25
15	8.2	10.59	11.7	13.3	13.66	15.43	16.06	19.7	26.4	29.5	33.55
Total	179.27	234.9	270.1	295.1	310.1	320.1	333.1	437.1	610.1	679.2	766.2

Table C17: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) Initial Bed Height = 12.0 cm Flowrate =8.9 Lit/ min

Temperature = 29 C Voidage = 0.55

CATHODE SECTION ↓	VOLTAGE (m V) → 50	100	150	200	250	300	350	400	450	500	550
1	8.64	11.68	13.53	16.1	18.19	19.53	19.66	24.8	34.2	40.1	43.02
2	7.88	10.73	13.33	15	17.39	19.43	19.66	24.6	33	39.9	42.82
3	7.88	10.13	12.83	14.5	17.19	17.93	18.56	23.4	31.9	37.9	40.82
4	7.64	10.53	12.83	14.5	16.39	16.93	17.66	22.5	31.9	37.6	40.52
5	7.64	10.53	12.83	14.5	16.39	16.93	17.76	22.6	31.9	37.6	40.52
6	26.31	34.93	39.37	44.4	45.36	45.12	44.84	65.7	86.6	95.4	107.2
7	25.23	33.46	39.33	44.4	45.36	43.82	43.64	63	85	93.2	105
8	24.55	32.92	38.78	41.1	42.86	41.12	40.74	62.6	84	91.8	103.6
9	24.11	31.93	37.82	40.1	42.26	41.02	41.14	61.7	84	91.8	103.6
10	24.8	22.84	37.62	38.1	38.36	37.02	38.34	58.5	85.1	81	92.8
11	7.62	9.89	10.46	.15	13.16	16.83	17.46	20.7	27.2	32	33
12	6.81	9.39	9.96	11.8	12.56	13.53	14.16	17.4	23.9	28.7	31.65
13	6.81	9.39	9.96	11.6	12.66	13.73	13.86	17.1	24.1	29.1	31.05
14	6.99	9.59	10.15	12	12.86	13.53	13.86	17.1	25.2	29.3	32.15
15	9.1	11.49	12.6	14.2	14.56	16.33	16.96	20.6	27.3	30.4	34.45
Total	202.01	259.4	311.4	347.3	365.55	372.8	378.3	522.3	715.5	795.8	882.2

Table C18: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) Initial Bed Height = 12.0 cm Flowrate = 10.5Lit/ min

Temperature = 29 C Voidage = 0.85

← V O L T A G E →
(m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	10.51	13.38	15.2	17.5	19.76	21.33	24.76	27.7	37.97	48.67	56.07
2	9.75	12.43	15	16.4	18.96	21.23	24.76	27.5	36.77	48.47	55.87
3	9.75	11.83	14.5	15.9	18.76	19.73	23.66	26.3	35.67	46.47	53.87
4	9.51	12.23	14.5	15.9	17.96	18.73	22.76	25.4	35.67	46.17	53.57
5	9.51	12.23	14.5	15.9	17.96	18.73	22.86	25.5	35.67	46.17	53.57
6	32.39	40.33	44.65	48.6	50.24	60.9	63.84	75.9	100.3	128.44	157.98
7	31.31	38.86	44.61	48.6	50.24	49.6	62.64	73.2	98.68	126.24	155.78
8	30.63	38.32	44.06	45.3	47.74	46.9	59.74	72.8	97.68	124.84	154.38
9	30.19	37.33	43.1	44.3	47.14	46.8	60.14	71.9	97.68	124.84	154.38
10	28.92	36.62	42.9	42.3	43.24	42.8	57.34	68.7	98.78	114.04	143.58
11	8.59	11.53	12.4	17.1	15.56	16.23	19.86	22.5	30.67	39.97	47.87
12	8.41	11.33	12.2	14.2	15.26	16.23	19.86	22.5	30.67	39.97	47.37
13	8.41	11.33	12.2	14	15.36	16.43	19.56	22.2	30.87	39.97	46.77
14	7.91	10.83	11.7	13.5	14.86	15.53	18.96	21.5	31.27	39.57	47.17
15	11.51	14.63	15.68	16.7	18.16	20.03	23.46	26.6	34.87	42.37	50.97
Total	247.3	313.2	357.2	386.2	411.2	421.2	524.2	610.2	833.2	1056.2	1279.2

Table C19: Local Current of Individual Section for Increasing Applied Voltage.

Particle Size = 1mm (dia) Initial Bed Height = 12.0 cm Flowrate =11.4 Lit/ min

Temperature = 29 C Voidage = 0.8

← V O L T A G E →
(m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	11.32	14.88	17	19.64	21.72	22.67	23.54	28.2	38.47	49.17	56.57
2	10.36	13.93	16.8	18.54	20.72	22.57	23.54	28	37.27	48.97	56.37
3	10.36	13.33	16.3	18.04	20.52	21.07	22.44	26.8	36.17	46.97	54.37
4	10.12	13.73	16.3	18.04	19.72	20.07	21.54	25.9	36.17	46.67	54.07
5	10.12	13.73	16.3	18.04	19.72	20.07	21.64	26	36.17	46.67	54.07
6	33.03	44.53	50.05	55.36	55.48	54.5	57.13	76.1	100.5	128.48	158.18
7	31.95	43.06	50.01	55.36	55.48	53.2	55.93	73.4	98.9	126.28	155.98
8	31.27	42.52	49.44	52.06	52.98	50.5	53.03	73	97.9	124.88	154.58
9	30.83	41.53	48.5	51.06	51.16	50.4	53.43	72.1	97.9	124.88	154.58
10	29.56	40.82	48.3	49.06	48.48	46.4	50.63	68.9	99	114.08	143.78
11	8.9	12.73	13.9	18.94	17.02	17.27	18.34	22.7	30.87	40.17	48.07
12	8.72	12.53	13.7	16.04	16.72	17.27	18.34	22.7	30.87	40.17	47.57
13	8.72	12.53	13.7	15.84	15.84	17.47	18.04	22.4	31.07	40.57	46.97
14	8.24	12.33	13.2	15.54	15.55	16.57	17.34	21.7	31.47	39.97	47.37
15	10.84	14.63	16.3	18.24	18.69	19.97	24.2	25.9	34.07	41.87	50.27
Total	254.34	346.8	399.8	439.8	445.8	450	479.11	613.8	836.8	1059.8	1282.8

Table C20: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) Initial Bed Height = 12.0 cm Flowrate = 12.7 Lit/ min

Temperature = 29 C Voidage = 0.8

← V O L T A G E → (m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	11.68	15.65	18.33	21.6	23.16	27.66	33.83	35.73	40.23	52.5	61.13
2	10.92	14.7	18.13	20.5	22.36	27.56	33.83	35.53	39.03	52.3	60.93
3	10.92	14.1	17.63	20	22.16	26.06	32.73	34.33	37.93	50.3	58.93
4	10.68	14.5	17.63	20	21.36	25.06	31.83	33.43	37.93	50	58.63
5	10.68	14.5	17.63	20	21.36	25.06	31.93	33.53	37.93	50	58.63
6	36.17	48.51	56.27	64.1	62.94	75.34	99.22	107.1	108.4	142.7	177.32
7	35.09	47.04	56.23	64.1	62.94	74.04	98.02	104.4	106.8	140.5	175.12
8	34.41	46.5	55.68	60.6	60.44	71.34	95.12	104	105.6	139.1	173.72
9	33.97	45.51	54.72	59.8	59.84	71.24	95.52	103.1	105.8	139.1	173.72
10	32.7	44.8	54.52	57.8	55.94	67.24	92.72	99.92	106.9	128.3	162.92
11	10.06	14.1	15.83	21.5	19.26	22.86	29.23	30.83	33.23	44.1	53.23
12	9.88	13.9	15.63	18.6	18.96	22.86	29.23	30.89	33.23	44.1	52.73
13	9.88	13.9	15.63	18.4	19.06	23.06	28.93	30.53	33.43	44.5	52.13
14	10.08	14.1	15.83	18.8	19.26	22.86	28.93	30.53	34.53	44.4	53.23
15	11.08	15	17.43	19.8	19.96	24.56	30.93	33.03	35.43	44.8	54.53
Total	278.2	376.8	447.12	505.8	509	606.8	792	846.9	896.7	1166.7	1426.9

Table C21: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) Initial Bed Height = 12.0 cm Flowrate = 14.6Lit/ min

Temperature = 29 C Voidage = 0.8

← V O L T A G E →
(m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	11.64	16.92	21	23.13	27.66	32.2	38.06	43.77	52.97	65.9	80.2
2	10.88	15.97	20.8	22.03	26.86	32.1	38.06	43.57	51.77	65.7	80
3	10.88	15.37	20.3	21.53	26.66	30.6	36.96	42.37	50.67	63.7	78
4	10.64	15.77	20.3	21.53	25.86	29.6	36.06	41.47	50.67	63.4	77.7
5	10.64	15.77	20.3	21.53	25.86	29.6	36.16	41.57	50.67	63.4	77.7
6	35.11	52.69	66.05	69.32	80.04	92.6	115.24	138.4	158.5	195.4	252.7
7	34.03	51.22	66.01	69.32	80.04	91.3	114.04	135.7	156.9	193.2	250.5
8	33.35	50.68	65.46	66.02	77.54	88.6	111.14	135.3	155.9	191.8	249.1
9	32.91	49.69	64.5	65.02	76.94	88.5	111.54	134.4	155.9	191.8	249.1
10	31.64	48.98	64.3	63.02	73.04	84.5	108.74	131.2	157	181	238.3
11	10.12	15.47	18.6	23.13	23.86	27.5	33.56	38.97	46.07	57.6	72.4
12	9.94	15.27	18.4	20.23	23.56	27.5	33.56	38.97	46.07	57.6	71.9
13	9.94	15.27	18.4	20.03	23.66	27.7	33.26	38.67	46.27	58	71.3
14	10.14	15.47	18.6	20.43	23.86	27.5	33.26	38.67	47.37	57.9	72.4
15	11.14	16.37	20.2	21.43	24.56	29.2	35.26	41.17	48.27	58.3	73.7
Total	273	410.9	523.22	547.7	640	739	914.9	1084	1275	1564.7	1995

Table C22: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) Initial Bed Height = 15.0 cm Flowrate = 5.8 Lit/ min

Temperature = 29 C Voidage = 0.75

← V O L T A G E → (m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	6.44	11.45	14.03	16.97	21.53	25.87	29.96	36.07	38.07	50.3	61.6
2	6.44	10.5	13.83	15.87	20.73	25.77	29.96	35.87	36.87	50.1	61.4
3	5.68	9.9	13.33	15.37	20.53	24.27	28.86	34.67	35.77	48.1	59.4
4	5.44	10.3	13.33	15.37	19.73	23.27	27.96	33.77	35.77	47.8	59.1
5	5.44	10.3	13.33	15.37	19.73	23.27	28.06	33.87	35.77	47.8	59.1
6	22.71	39.21	46.57	53.08	63.92	75.68	91.24	116	107.3	141.4	186.7
7	21.63	37.74	46.53	53.08	63.92	74.38	90.04	113.3	105.7	139.2	184.5
8	20.95	37.2	45.98	49.78	61.42	71.68	87.14	112.9	104.7	137.8	183.1
9	20.51	36.21	45.02	48.78	60.82	71.58	87.54	112	104.7	137.8	183.1
10	17.34	33.6	42.92	44.88	55.02	65.68	82.84	106.9	103.9	125.1	170.4
11	5.82	10.9	12.53	17.87	18.63	22.07	26.36	32.17	32.07	42.9	54.7
12	5.64	10.7	12.33	14.97	18.33	22.07	26.36	32.17	32.07	42.9	54.2
13	5.64	10.7	12.33	14.77	18.43	22.27	26.06	31.87	32.27	43.3	53.6
14	5.84	10.9	12.53	15.17	18.63	22.07	26.06	31.87	33.37	43.2	54.7
15	6.84	11.8	14.13	16.17	19.33	23.77	28.06	34.37	34.27	43.6	56
Total	162.36	291.4	358.72	407.5	500.7	593.7	716.5	897.7	872.5	1141.3	1481.6

Table C23: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) Initial Bed Height = 15.0 cm Flowrate =7.9 Lit/ min

Temperature = 29 C Voidage = 0.75

VOLTAGE (m V) ⟶

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	6.71	9.24	10.76	12.9	14.86	16.43	16.86	20.4	29	35.3	38.15
2	5.95	8.29	10.56	11.8	14.06	16.33	16.86	20.2	27.8	35.1	37.95
3	5.95	7.69	10.06	11.3	13.86	14.83	15.76	19	26.7	33.1	35.95
4	5.71	8.09	10.06	11.3	13.06	13.83	14.86	18.1	26.7	32.8	35.65
5	5.71	8.09	10.06	11.3	13.06	13.83	14.96	18.2	26.7	32.8	35.65
6	17.09	23.68	26.82	30.1	30.54	31.22	32.14	46.6	64.3	70	81.5
7	16.01	22.41	26.78	30.1	30.54	29.92	30.94	43.9	62.7	67.8	79.3
8	15.33	21.67	26.23	26.8	28.04	27.22	28.04	43.5	61.7	66.4	77.9
9	12.99	18.78	23.37	23.9	25.54	25.22	26.54	40.7	59.8	64.5	76
10	9.62	15.97	21.07	19.8	19.54	19.12	21.64	35.4	58.8	53.7	65.2
11	5.29	7.89	8.46	13	11.16	11.83	12.46	15.7	22.2	27	30.45
12	5.11	7.69	8.26	10.1	10.86	11.83	12.46	15.7	22.2	27	29.95
13	5.11	7.69	8.26	9.9	10.96	12.03	12.16	15.4	22.4	27.4	29.35
14	5.29	7.89	8.45	10.3	11.16	11.83	12.16	15.4	23.5	27.6	30.45
15	6.4	8.79	9.9	11.5	11.86	13.63	14.26	17.9	24.6	27.7	31.75
Total	128.27	183.9	219.1	244.1	259.1	269.1	282.1	386.1	559.1	628.2	715.2

Table C24: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) Initial Bed Height = 15.0 cm Flowrate = 8.7 Lit/ min

Temperature = 29 C Voidage = 0.75

VOLTAGE (m A) →

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	6.34	9.38	11.23	13.8	15.89	17.23	17.36	22.5	31.9	37.8	40.72
2	5.58	8.43	11.03	12.7	15.09	17.13	17.36	22.3	30.7	37.6	40.52
3	5.58	7.83	10.53	12.2	14.89	15.63	16.26	21.1	29.6	35.6	38.52
4	5.34	8.23	10.53	12.2	14.09	14.63	15.36	20.2	29.6	35.3	38.22
5	5.34	8.23	10.53	12.2	14.09	14.63	15.46	20.3	29.6	35.3	38.22
6	20.91	29.53	33.97	39	39.96	39.72	39.44	60.3	81.2	90	101.8
7	19.83	28.06	33.93	39	39.96	38.42	38.24	57.6	79.6	87.8	99.6
8	19.15	27.52	33.38	35.7	37.46	35.72	35.34	57.2	78.6	86.4	98.2
9	18.71	26.53	32.42	34.7	36.86	35.62	35.74	56.3	78.6	86.4	98.2
10	19.4	17.44	32.22	32.7	32.96	31.62	32.94	53.1	79.7	75.6	87.4
11	6.22	8.49	9.06	13.6	11.76	15.43	16.06	19.3	25.8	30.6	31.6
12	5.41	7.99	8.56	10.4	11.16	12.13	12.76	16	22.5	27.3	30.25
13	5.41	7.99	8.56	10.2	11.26	12.33	12.46	15.7	22.7	27.7	29.65
14	5.59	8.19	8.75	10.6	11.46	12.13	12.46	15.7	23.8	27.9	30.75
15	7.7	10.09	11.2	12.8	13.16	14.93	15.56	19.2	25.9	29	33.05
Total	156.51	213.9	265.9	301.8	320.05	327.3	332.8	476.8	669.8	750.3	836.7

Table C25: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) Initial Bed Height = 15.0 cm Flowrate = 10.5 Lit/ min

Temperature = 29 C Voidage = 0.75

← V O L T A G E →
(m A)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	8.01	10.88	12.7	15	17.26	18.83	22.26	25.2	35.47	46.17	53.57
2	7.25	9.93	12.5	13.9	16.46	18.73	22.26	25	34.27	45.97	53.37
3	7.25	9.33	12	13.4	16.26	17.23	21.16	23.8	33.17	43.97	51.37
4	7.01	9.73	12	13.4	15.46	16.23	20.26	22.9	33.17	43.67	51.07
5	7.01	9.73	12	13.4	15.46	16.23	20.36	23	33.17	43.67	51.07
6	27.89	35.83	40.15	44.1	45.74	46.4	59.34	71.4	95.78	123.94	153.48
7	26.81	34.36	40.11	44.1	45.74	45.1	58.14	68.7	94.18	121.74	151.28
8	26.13	33.82	39.56	40.8	43.24	42.4	55.24	68.3	93.18	120.34	149.88
9	25.69	32.83	38.6	39.8	42.64	42.3	55.64	67.4	93.18	120.34	149.88
10	24.42	32.12	38.4	37.8	38.74	38.3	52.84	64.2	94.28	109.54	139.08
11	6.09	9.03	9.9	14.6	13.06	13.73	17.36	20	28.17	37.47	45.37
12	5.91	8.83	9.7	11.7	12.76	13.73	17.36	20	28.17	37.47	44.87
13	5.91	8.83	9.7	11.5	12.86	13.93	17.06	19.7	28.37	37.47	44.27
14	5.41	8.33	9.2	11	12.36	13.03	16.46	19	28.77	37.07	44.67
15	9.01	12.13	13.18	14.2	15.66	17.53	20.96	24.1	32.37	39.87	48.47
Total	199.8	265.7	309.7	338.7	363.7	373.7	476.7	562.7	785.7	1008.7	1231.7

Table C26: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia)   Initial Bed Height = 15.0 cm   Flowrate = 11.4 Lit/ min

Temperature = 29 C   Voidage = 0.75

VOLTAGE (m V)

CATHODE SECTION	50	100	150	200	250	300	350	400	450	500	550
1	8.72	12.28	14.4	17.04	19.12	20.07	20.94	25.6	35.87	46.57	53.97
2	7.76	11.33	14.2	15.94	18.12	19.97	20.94	25.4	34.67	46.37	53.77
3	7.76	10.73	13.7	15.44	17.92	18.47	19.84	24.2	33.57	44.37	51.77
4	7.52	11.13	13.7	15.44	17.12	17.47	18.94	23.3	33.57	44.07	51.47
5	7.52	11.13	13.7	15.44	17.12	17.47	19.04	23.4	33.57	44.07	51.47
6	30.43	41.93	47.45	52.76	52.88	51.9	54.53	73.5	97.9	125.88	155.58
7	29.35	40.46	47.41	52.76	52.88	50.6	53.33	70.8	96.3	123.68	153.38
8	28.67	39.92	46.84	49.46	50.38	47.9	50.43	70.4	95.3	122.28	151.98
9	28.23	38.93	45.9	48.46	48.56	47.8	50.83	69.5	95.3	122.28	151.98
10	26.96	38.22	45.7	46.46	45.88	43.8	48.03	66.3	96.4	111.48	141.18
11	6.3	10.13	11.3	16.34	14.42	14.67	15.74	20.1	23.27	37.57	45.47
12	6.12	9.93	11.1	13.44	14.12	14.67	15.74	20.1	23.27	37.57	44.97
13	6.12	9.93	11.1	13.24	13.24	14.87	15.44	19.8	28.47	37.97	44.37
14	5.64	9.73	10.6	12.94	12.95	13.97	14.74	19.1	28.87	37.37	44.77
15	8.24	12.03	13.7	15.64	16.09	17.37	21.6	23.3	31.47	39.27	47.67
Total	215.34	307.8	360.8	400.8	410.8	411	440.11	574.8	797.8	1020.8	1243.8

Table C27: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) Initial Bed Height = 15.0 cm Flowrate = 12.7 Lit/ min

Temperature = 29 C Voidage = 0.75

← V O L T A G E →
(m V)

CATHODE SECTION	50	100	150	200	250	300	350	400	450	500	550
1	9.08	13.05	15.73	19	20.56	25.06	31.23	33.13	37.63	49.9	58.53
2	8.32	12.1	15.53	17.9	19.76	24.56	31.23	32.93	36.43	49.7	58.33
3	8.32	11.5	15.03	17.4	19.56	23.46	30.13	31.73	35.33	47.7	56.33
4	8.08	11.9	15.03	17.4	18.76	22.46	29.23	30.83	35.33	47.4	56.03
5	8.08	11.9	15.03	17.4	18.76	22.46	29.33	30.93	35.33	47.4	56.03
6	29.57	41.91	49.67	57.5	56.34	68.74	92.62	100.5	101.8	136.1	170.72
7	28.49	40.44	49.63	57.5	56.34	67.44	91.42	97.82	100.2	133.9	168.52
8	27.81	39.9	49.08	54.2	53.84	64.74	88.52	97.42	99.22	132.5	167.12
9	27.37	38.91	48.12	53.2	53.24	64.64	88.92	96.52	99.22	132.5	167.12
10	26.1	38.2	47.92	51.2	49.34	60.64	86.12	93.32	100.3	121.7	156.32
11	7.46	11.5	13.23	18.9	16.66	20.26	26.63	28.23	30.63	41.5	50.63
12	7.28	11.3	13.03	16	16.36	20.26	26.63	28.23	30.63	41.5	50.13
13	7.28	11.3	13.03	15.8	16.46	20.46	26.33	27.93	30.83	41.9	49.53
14	7.48	11.5	13.23	16.2	16.66	20.26	26.33	27.93	31.93	41.8	50.63
15	8.48	12.4	14.83	17.2	17.36	21.96	28.33	30.43	32.83	42.2	51.93
Total	219.2	317.8	388.12	446.8	450	547.8	733	787.9	837.7	1107.7	1367.9

Table C28: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 1mm (dia) Initial Bed Height = 15.0 cm Flowrate = 14.6Lit/min

Temperature = 29 C Voidage = 0.75

← V O L T A G E → (m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	6.78	10.75	13.43	16.7	18.26	22.76	28.93	30.83	35.33	47.6	56.23
2	6.02	9.8	13.23	15.6	17.46	22.66	28.93	30.63	34.13	47.4	56.03
3	6.02	9.2	12.73	15.1	17.26	21.16	27.83	29.43	33.03	45.4	54.03
4	5.78	9.6	12.73	15.1	16.46	20.16	26.93	28.53	33.03	45.1	53.73
5	5.78	9.6	12.73	15.1	16.46	20.16	27.03	28.63	33.03	45.1	53.73
6	24.27	36.61	44.37	52.2	51.04	63.44	87.32	95.22	96.52	130.8	165.42
7	23.19	35.14	44.33	52.2	51.04	62.14	86.12	92.52	94.92	128.6	163.22
8	22.51	34.6	43.78	48.9	48.54	59.44	83.22	92.12	93.92	127.2	161.82
9	22.07	33.61	42.82	47.9	47.94	59.34	83.62	91.22	93.92	127.2	161.82
10	20.8	32.9	42.62	45.9	44.04	55.34	80.82	88.02	95.02	116.4	151.02
11	5.16	9.2	10.93	16.6	14.36	17.96	24.33	25.93	28.33	39.2	48.33
12	4.98	9	10.73	13.7	14.06	17.96	24.33	25.93	28.33	39.2	47.83
13	4.98	9	10.73	13.5	14.16	18.16	24.03	25.63	28.53	39.6	47.23
14	5.18	9.2	10.93	13.9	14.36	17.96	24.03	25.63	29.63	39.5	48.33
15	6.18	10.1	12.53	14.9	15.06	19.66	26.03	28.13	30.53	39.9	49.63
Total	169.7	268.3	338.62	397.3	400.5	498.3	683.5	738.4	783.2	1058.2	1318.4

Table C29: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 2mm (dia) Initial Bed Height = 6.0 cm Flowrate = 5.8 Lit/ min

Temperature = 29 C Voidage = 0.9

SECTION	VOLTAGE (m V) → 50	100	150	200	250	300	350	400	450	500	550
1	5.49	7.8	9.35	11.25	13.15	14.75	15.05	15.35	22.85	29.35	34.05
2	4.73	6.85	9.15	10.15	12.35	14.65	15.05	15.15	21.65	29.15	33.85
3	4.73	6.25	8.65	9.65	12.15	13.15	13.95	13.95	20.55	27.15	31.85
4	4.49	6.65	8.65	9.65	11.35	12.15	13.05	13.05	20.55	26.85	31.55
5	4.49	6.65	8.65	9.65	11.35	12.15	13.15	13.15	20.55	26.85	31.55
6	12.66	18.36	21.6	23.95	24.15	24.95	25.35	26.85	40.15	51.35	70.25
7	11.58	16.89	21.56	23.95	24.15	23.65	24.15	24.15	38.55	49.15	68.05
8	10.9	16.35	21.01	20.65	21.65	20.95	21.25	23.75	37.55	47.75	66.65
9	10.46	15.36	20.05	19.65	21.05	20.85	21.65	22.85	37.55	47.75	66.65
10	9.19	14.65	19.85	17.65	17.15	16.85	18.85	19.65	38.65	36.95	55.85
11	4.37	6.75	7.35	11.65	9.75	10.45	10.95	10.95	16.35	21.45	26.65
12	4.19	6.55	7.15	8.75	9.45	10.45	10.95	10.95	16.35	21.45	26.15
13	4.19	6.55	7.15	8.55	9.55	10.65	10.65	10.65	16.55	21.85	25.55
14	4.39	6.75	7.35	8.95	9.75	10.45	10.65	10.65	17.65	21.75	26.65
15	5.39	7.65	8.95	9.95	10.45	12.15	12.65	13.15	18.55	22.15	27.95
Total	101.25	150.1	186.47	204.05	217.45	228.3	237.35	244.3	384.1	480.95	623.25

Table C30: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 2mm (dia) Initial Bed Height = 6.0 cm Flowrate = 7.9 Lit/ min

Temperature = 29 C Voidage = 0.9

← V O L T A G E →
(m V)

CATHODE SECTION ↓		50	100	150	200	250	300	350	400	450	500	550
	1	5.76	8.29	9.81	11.95	13.91	15.48	15.91	19.45	28.05	34.35	37.2
	2	5	7.34	9.61	10.85	13.11	15.38	15.91	19.25	26.85	34.15	37
	3	5	6.74	9.11	10.35	12.91	13.88	14.81	18.05	25.75	32.15	35
	4	4.76	7.14	9.11	10.35	12.11	12.88	13.91	17.15	25.75	31.85	34.7
	5	4.76	7.14	9.11	10.35	12.11	12.88	14.01	17.25	25.75	31.85	34.7
	6	13.44	20.03	23.17	26.45	26.89	27.57	28.49	42.95	60.65	71.05	82.55
	7	12.36	18.76	23.13	26.45	26.89	26.27	27.29	40.25	59.05	68.85	80.35
	8	11.68	18.02	22.58	23.15	24.39	23.57	24.39	39.85	58.05	67.45	78.95
	9	11.24	17.03	21.62	22.15	23.79	23.47	24.79	38.95	58.05	67.45	78.95
	10	9.97	16.32	21.42	20.15	19.89	19.47	21.99	35.75	59.15	56.65	68.15
	11	4.64	7.24	7.81	12.35	10.51	11.18	11.81	15.05	21.55	26.35	29.8
	12	4.46	7.04	7.61	9.45	10.21	11.18	11.81	15.05	21.55	26.35	29.3
	13	4.46	7.04	7.61	9.25	10.31	11.38	11.51	14.75	21.75	26.75	28.7
	14	4.64	7.24	7.8	9.65	10.51	11.18	11.51	14.75	22.85	26.95	29.8
	15	5.75	8.14	9.25	10.85	11.21	12.98	13.61	17.25	23.95	27.05	31.1
Total		107.92	163.5	198.75	223.75	238.75	248.8	261.75	365.8	538.8	629.25	716.25

Table C31: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 2 mm (dia) Initial Bed Height = 6.0 cm Flowrate = 8.9 Lit/ min

Temperature = 29 C Voidage = 0.9

		VOLTAGE (m V)										
		50	100	150	200	250	300	350	400	450	500	550
CATHODE SECTION	1	6.18	9.22	11.07	13.64	15.73	17.07	17.2	22.34	31.74	37.64	40.56
	2	5.42	8.27	10.87	12.54	14.93	16.97	17.2	22.14	30.54	37.44	40.36
	3	5.42	7.67	10.37	12.04	14.73	15.47	16.1	20.94	29.44	35.44	38.36
	4	5.18	8.07	10.37	12.04	13.93	14.47	15.2	20.04	29.44	35.14	38.06
	5	5.18	8.07	10.37	12.04	13.93	14.47	15.3	20.14	29.44	35.14	38.06
	6	13.35	21.97	26.41	31.44	32.4	32.16	31.88	52.74	73.64	82.44	94.24
	7	12.27	20.5	26.37	31.44	32.4	30.86	30.68	50.04	72.04	80.24	92.04
	8	11.59	19.96	25.82	28.14	29.9	28.16	27.78	49.64	71.04	78.84	90.64
	9	11.15	18.97	24.86	27.14	29.3	28.06	28.18	48.74	71.04	78.84	90.64
	10	9.88	18.26	24.66	25.14	25.4	24.06	25.38	45.54	72.14	68.04	79.84
	11	5.06	8.17	9.07	14.04	12.33	12.77	13.1	17.94	25.24	29.74	33.16
	12	4.88	7.97	8.87	11.14	12.03	12.77	13.1	17.94	25.24	29.74	32.66
	13	4.88	7.97	8.87	10.94	12.13	12.97	12.8	17.64	25.44	30.14	32.06
	14	5.08	8.47	8.95	11.54	12.33	12.87	12.9	17.64	26.54	30.04	33.16
↓	15	6.08	9.07	10.67	12.34	13.13	14.47	14.8	20.14	27.64	30.74	34.26
Total		111.6	182.6	227.6	265.6	284.6	287.6	291.6	443.6	640.6	719.6	808.1

Table C32: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 2 mm (dia) Initial Bed Height = 6.0 cm Flowrate = 10.5 ℓ/min

Temperature = 29 C Voidage = 0.9

		VOLTAGE (m V)										
		50	100	150	200	250	300	350	400	450	500	550
CATHODE SECTION	1	7.45	10.32	12.14	14.44	16.7	18.27	21.7	24.64	34.91	45.61	53.01
	2	6.69	9.37	11.94	13.34	15.9	18.17	21.7	24.44	33.71	45.41	52.81
	3	6.69	8.77	11.44	12.84	15.7	16.67	20.6	23.24	32.61	43.41	50.81
	4	6.45	9.17	11.44	12.84	14.9	15.67	19.7	22.34	32.61	43.11	50.51
	5	6.45	9.17	11.44	12.84	14.9	15.67	19.8	22.44	32.61	43.11	50.51
	6	19.33	27.27	31.59	35.54	37.18	37.84	50.78	62.84	87.22	115.38	144.92
	7	18.25	25.8	31.55	35.54	37.18	36.54	49.58	60.14	85.62	113.18	142.72
	8	17.57	25.26	31	32.24	34.68	33.84	46.68	59.74	84.62	111.78	141.32
	9	17.13	24.27	30.04	31.24	34.08	33.74	47.08	58.84	84.62	111.78	141.32
	10	15.86	23.56	29.84	29.24	30.18	29.74	44.28	55.64	85.72	100.98	130.52
	11	6.33	9.27	10.14	14.84	13.3	13.97	17.6	20.24	28.41	37.71	45.61
	12	6.15	9.07	9.94	11.94	13	13.97	17.6	20.24	28.41	37.71	45.11
	13	6.15	9.07	9.94	11.74	13.1	14.17	17.3	19.94	28.61	37.71	44.51
	14	6.35	9.27	10.14	11.94	13.3	13.97	17.4	19.94	29.71	38.01	45.61
	15	7.35	10.47	11.52	12.54	14	15.87	19.3	22.44	30.71	38.21	46.81
Total		154.2	220.1	264.1	293.1	318.1	328.1	431.1	517.1	740.1	963.1	1186.1

Table C33: Local Current of Individual Section for increasing Applied Voltage

Particle Size = 2 mm (dia) Initial Bed Height = 6.0 cm Flowrate = 11.4 Lit/ min

Temperature = 29 C Voidage = 0.9

CATHODE SECTION	VOLTAGE (m V) → 50	100	150	200	250	300	350	400	450	500	550
1	7.84	11.4	13.52	16.16	18.24	19.19	20.06	24.72	34.99	45.69	53.09
2	6.88	10.45	13.32	16.06	17.24	19.09	20.06	24.52	33.79	45.49	52.89
3	6.88	9.85	12.82	14.56	17.04	17.59	18.96	23.32	32.69	43.49	50.89
4	6.64	10.25	12.82	14.56	16.24	16.59	18.06	22.42	32.69	43.19	50.59
5	6.64	10.25	12.82	14.56	16.24	16.59	18.16	22.52	32.69	43.19	50.59
6	19.85	31.35	36.87	42.18	42.3	41.32	43.95	62.92	87.32	115.3	145
7	18.77	29.88	36.83	42.18	42.3	40.02	42.75	60.22	85.72	113.1	142.8
8	18.09	29.34	36.26	38.88	39.8	37.32	39.85	59.82	84.72	111.7	141.4
9	17.65	28.35	35.32	37.88	37.98	37.22	40.25	58.92	84.72	111.7	141.4
10	16.38	27.64	35.12	35.88	35.3	33.22	37.45	55.72	85.82	100.9	130.6
11	6.52	10.35	11.52	16.56	14.64	14.89	15.96	20.32	28.49	37.79	45.69
12	6.34	10.15	11.32	13.66	14.34	14.89	15.96	20.32	28.49	37.79	45.19
13	6.34	10.15	11.32	13.46	13.46	15.09	15.66	20.02	28.69	38.19	44.59
14	6.56	10.65	11.52	13.86	13.87	14.89	15.66	20.02	29.79	38.29	45.69
15	7.46	11.25	12.92	14.86	15.31	16.59	20.82	22.52	30.69	38.49	46.89
Total	158.84	251.3	304.3	344.3	364.3	354.5	383.61	518.3	741.3	964.3	1187.3

Table C34: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 2mm (dia) Initial Bed Height = 6.0 cm Flowrate = 12.7 Lit/ min

Temperature = 29 C Voidage = 0.9

← V O L T A G E →
(m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	7.95	11.92	14.6	17.87	19.43	23.93	30.1	32	36.5	48.77	57.4
2	7.19	10.97	14.4	16.77	18.63	23.83	30.1	31.8	35.3	48.57	57.2
3	7.19	10.37	13.9	16.27	18.43	22.33	29	30.6	34.2	46.57	55.2
4	6.95	10.77	13.9	16.27	17.63	21.33	28.1	29.7	34.2	46.27	54.9
5	6.95	10.77	13.9	16.27	17.63	21.33	28.2	29.8	34.2	46.27	54.9
6	21.84	34.18	41.94	49.77	48.61	61.01	84.89	92.79	94.09	128.37	162.99
7	20.76	32.71	41.9	49.77	48.61	59.71	83.69	90.09	92.49	126.17	160.79
8	20.08	32.17	41.35	46.47	46.11	57.01	80.79	89.69	91.49	124.77	159.39
9	19.64	31.18	40.39	45.47	45.51	56.91	81.19	88.79	91.49	124.77	159.39
10	18.37	30.47	40.19	43.47	41.61	52.91	78.39	85.59	92.59	113.97	148.59
11	6.83	10.87	12.6	18.27	16.03	19.63	26	27.6	30	40.87	50
12	6.65	10.67	12.4	15.37	15.73	19.63	26	27.6	30	40.87	49.5
13	6.65	10.67	12.4	15.17	15.83	19.83	25.7	27.3	30.2	41.27	48.9
14	6.85	10.87	12.6	15.57	16.03	19.63	25.7	27.3	31.3	41.17	50
15	7.85	11.77	14.2	16.57	16.73	21.33	27.7	29.8	32.2	41.57	51.3
Total	171.75	270.4	340.67	399.35	402.55	500.4	685.55	740.5	790.3	1060.3	1320.5

Table C35: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 2mm (dia) Initial Bed Height = 6.0 cm Flowrate = 14.6 Lit/ min

Temperature = 29 C Voidage = 0.9

← V O L T A G E (m V) →

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	9.34	17.32	22.43	25.6	32.79	40.07	49.72	61.24	64.94	83.6	104.5
2	8.58	16.37	22.23	24.5	31.99	39.97	49.72	61.04	63.74	83.4	104.3
3	8.58	15.77	21.73	24	31.79	38.47	48.62	59.84	62.64	81.4	102.3
4	8.34	16.17	21.73	24	30.99	37.47	47.72	58.94	62.64	81.1	102
5	8.34	16.17	21.73	24	30.99	37.47	47.82	59.04	62.64	81.1	102
6	31.51	59.89	77.37	84.8	106.16	129.7	167.48	213.9	212	271.8	355.5
7	30.43	58.42	77.33	84.8	106.16	128.4	166.28	211.2	210.4	269.6	353.3
8	29.75	57.83	76.78	81.5	103.66	125.7	163.38	210.8	205.4	268.2	351.9
9	29.31	56.89	75.82	80.5	103.06	125.6	163.78	209.9	209.4	268.2	351.9
10	28.04	56.18	75.62	78.5	99.16	121.6	160.98	206.7	210.5	257.4	341.1
11	8.22	16.27	20.43	26	29.39	35.77	45.62	56.84	58.44	75.7	97.1
12	8.04	16.07	20.23	23.1	29.09	35.77	45.62	56.84	58.44	75.7	96.6
13	8.04	16.07	20.23	22.9	29.19	35.97	45.32	56.54	58.64	76.1	96
14	8.24	16.27	20.43	23.3	29.39	35.77	45.32	56.54	59.74	76	97.1
15	9.24	17.17	22.03	24.3	30.09	37.47	47.32	59.04	60.64	76.4	98.4
Total	234	452.9	596.12	651.8	823.9	1005	1294.7	1638	1664	2125.7	2754

Table C36: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 2mm (dia) Initial Bed Height = 9.0 cm Flowrate = 6.8 Lit/ min

Temperature = 29 C Voidage = 0.85

← V O L T A G E →
(m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	8.74	16.45	20.06	24.04	31.26	38.34	46.22	58.14	54.64	72.6	90.5
2	7.98	15.5	19.86	22.94	30.46	38.24	46.22	57.94	53.44	72.4	90.3
3	7.98	14.9	19.36	22.44	30.26	36.74	45.12	56.74	52.34	70.4	88.3
4	7.74	15.3	19.36	22.44	29.46	35.74	44.22	55.84	52.34	70.1	88
5	7.74	15.3	19.36	22.44	29.46	35.74	44.32	55.94	52.34	70.1	88
6	29.11	56.41	67.89	78.56	100.04	122.8	153.48	201.5	170.8	227.8	299.5
7	28.03	54.94	67.85	78.56	100.04	121.5	152.28	198.8	169.2	225.6	297.3
8	27.35	54.4	67.3	75.26	97.54	118.8	149.38	196.4	168.2	224.2	295.9
9	26.91	53.41	66.34	74.26	96.94	118.7	149.78	197.5	168.2	224.2	295.9
10	25.64	52.7	66.14	72.26	93.04	114.7	146.98	194.3	159.3	213.4	285.1
11	7.62	15.4	18.06	24.44	27.86	34.04	42.12	53.74	48.14	64.7	83.1
12	7.44	15.2	17.86	21.54	27.56	34.04	42.12	53.74	48.14	64.7	82.6
13	7.44	15.2	17.86	21.34	27.66	34.24	41.82	53.44	48.34	65.1	82
14	7.64	15.4	18.06	21.74	27.86	34.04	41.82	53.44	49.44	65	83.1
15	8.64	16.3	19.66	22.74	28.56	35.74	43.82	55.94	50.34	65.4	84.4
Total	216	426.8	525.02	605	778	953.2	1189.7	1545	1355	1795.7	2334

Table C37: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 2mm (dia) Initial Bed Height = 9.0 cm Flowrate = 7.9 Lit/ min

Temperature = 29 C Voidage = 0.85

CATHODE SECTION	VOLTAGE (m V) → 50	100	150	200	250	300	350	400	450	500	550
1	8.91	11.44	12.96	15.1	17.06	18.63	19.06	22.6	31.2	37.5	40.35
2	8.15	10.49	12.76	14	16.26	18.53	19.06	22.4	30	37.3	40.15
3	8.15	9.89	12.26	13.5	16.06	17.03	17.96	21.2	28.9	35.3	38.15
4	7.91	10.29	12.26	13.5	15.26	16.03	17.06	20.3	28.9	35	37.85
5	7.91	10.29	12.26	13.5	15.26	16.03	17.16	20.4	28.9	35	37.85
6	17.59	24.18	27.32	30.5	31.04	31.72	32.64	47.1	64.8	75.2	86.7
7	16.51	22.91	27.28	30.6	31.04	30.42	31.44	44.4	63.2	73	84.5
8	15.83	22.17	26.73	27.3	28.54	27.72	28.54	44	62.2	71.6	83.1
9	13.49	19.28	23.87	24.4	26.04	25.72	27.04	41.2	60.3	69.7	81.2
10	12.22	18.57	23.67	22.4	22.14	21.72	24.24	38	61.4	58.9	70.4
11	6.59	9.19	9.76	14.3	12.46	13.13	13.76	17	23.5	28.3	31.75
12	6.41	8.99	9.56	11.4	12.16	13.13	13.76	17	23.5	28.3	31.25
13	6.41	8.99	9.56	11.2	12.26	13.33	13.46	16.7	23.7	28.7	30.65
14	6.59	9.19	9.75	11.6	12.46	13.13	13.46	16.7	24.8	28.9	31.75
15	7.7	10.09	11.2	12.8	13.16	14.93	15.56	19.2	25.9	29	33.05
Total	150.37	206	241.2	266.2	281.2	291.2	304.2	408.2	581.2	671.7	758.7

Table C38: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 2mm (dia) Initial Bed Height = 9.0 cm Flowrate = 3.9 Lit/ min

Temperature = 29 C Voidage = 0.61

VOLTAGE (m V)

CATHODE SECTION	50	100	150	200	250	300	350	400	450	500	550
1	8.14	11.18	13.03	15.6	17.69	19.03	19.16	24.3	33.7	39.6	42.52
2	7.38	10.23	12.83	14.5	16.89	18.93	19.16	24.1	32.5	39.4	42.32
3	7.38	9.63	12.33	14	16.69	17.43	18.06	22.9	31.4	37.4	40.32
4	7.14	10.03	12.33	14	15.89	16.43	17.16	22	31.4	37.1	40.02
5	7.14	10.03	12.33	14	15.89	16.43	17.26	22.1	31.4	37.1	40.02
6	20.81	29.43	33.87	38.9	39.86	39.62	39.34	60.2	81.1	89.9	101.7
7	19.73	27.96	33.83	38.9	39.86	38.32	38.14	57.5	79.5	87.7	99.5
8	19.05	27.42	33.28	35.6	37.36	35.62	35.24	57.1	78.5	86.3	98.1
9	18.61	26.43	32.32	34.6	36.76	35.52	35.64	56.2	78.5	86.3	98.1
10	19.3	17.34	32.12	32.6	32.86	31.52	32.84	53	79.6	75.5	87.3
11	7.22	9.49	10.06	14.6	12.76	16.43	17.06	20.3	26.8	31.6	32.6
12	6.71	9.29	9.86	11.7	12.46	13.43	14.06	17.3	23.8	28.6	31.55
13	6.71	9.29	9.86	11.5	12.56	13.63	13.76	17	24	29	30.95
14	6.89	9.49	10.05	11.9	12.76	13.43	13.76	17	25.1	29.2	32.05
15	8	10.39	11.5	13.1	13.46	15.23	15.86	19.5	26.2	29.3	33.35
Total	170.21	227.6	279.6	315.5	333.75	341	346.5	490.5	683.5	764	850.4

Table C39: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 2mm (dia) Initial Bed Height = 9.0 cm Flowrate= 10.5 Lit/ min

Temperature = 29 C Voidage = 0.85

CATHODE SECTION ↓	VOLTAGE (m V) → 50	100	150	200	250	300	350	400	450	500	550
1	10.31	13.18	15	17.3	19.56	21.13	24.56	27.5	37.77	48.47	55.87
2	9.55	12.23	14.8	16.2	18.76	21.03	24.56	27.3	36.57	48.27	55.67
3	9.55	11.63	14.3	15.7	18.56	19.53	23.46	26.1	35.47	46.27	53.67
4	9.31	12.03	14.3	15.7	17.76	18.53	22.56	25.2	35.47	45.97	53.37
5	9.31	12.03	14.3	15.7	17.76	18.53	22.66	25.3	35.47	45.97	53.37
6	28.39	36.33	40.65	44.6	46.24	46.9	59.84	71.9	96.28	124.44	153.98
7	27.31	34.86	40.61	44.6	46.24	45.6	58.64	69.2	94.68	122.24	151.78
8	26.63	34.32	40.06	41.3	43.74	42.9	55.74	68.8	93.68	120.84	150.38
9	26.19	33.33	39.1	40.3	43.14	42.8	56.14	67.9	93.68	120.84	150.38
10	24.92	32.62	38.9	38.3	39.24	38.8	53.34	64.7	94.78	110.04	139.58
11	8.59	11.53	12.4	17.1	15.56	16.23	19.86	22.5	30.67	39.97	47.87
12	8.41	11.33	12.2	14.2	15.26	16.23	19.86	22.5	30.67	39.97	47.37
13	8.41	11.33	12.2	14	15.36	16.43	19.56	22.2	30.87	39.97	46.77
14	8.61	11.53	12.4	14.2	15.56	16.23	19.66	22.2	31.97	40.27	47.87
15	11.21	14.33	15.38	16.4	17.86	19.73	23.16	26.3	34.57	42.07	50.67
Total	226.7	292.6	336.6	365.6	390.6	400.6	503.6	589.6	812.6	1035.6	1258.6

Table C40: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 2 mm (dia) Initial Bed Height = 9.0 cm Flowrate =11.4 Lit/ min

Temperature = 29 C Voidage = 0.85

VOLTAGE (m V) →

Cathode Section	50	100	150	200	250	300	350	400	450	500	550
1	11.02	17.28	20.43	24.11	28.85	32.54	37.2	47.67	52.44	68.87	82.87
2	10.06	16.33	20.23	23.01	27.85	32.44	37.2	47.47	51.24	68.67	82.67
3	10.06	15.73	19.73	22.51	27.65	30.94	36.1	46.27	50.14	66.67	80.67
4	9.82	16.13	19.73	22.51	26.85	29.94	35.2	45.37	50.14	66.37	80.37
5	9.82	16.13	19.73	22.51	26.85	29.94	35.3	45.47	50.14	66.37	80.37
6	35.03	57.33	66.97	76.44	87.2	97.18	114.97	157.2	159.6	210.48	266.58
7	33.95	55.86	66.93	76.44	87.2	95.88	113.77	154.5	158	208.28	264.38
8	33.27	55.32	66.36	73.14	84.7	93.18	110.87	154.1	157	206.88	262.98
9	32.83	54.33	65.42	72.14	82.88	93.08	111.27	153.2	157	206.88	262.98
10	31.56	53.62	65.22	70.14	80.2	89.08	108.47	150	158.1	196.08	252.18
11	8.9	15.43	17.63	23.71	24.45	27.44	32.3	42.47	45.14	60.17	74.67
12	8.72	15.23	17.43	20.81	24.15	27.44	32.3	42.47	45.14	60.17	74.17
13	8.72	15.23	17.43	20.61	23.27	27.64	32	42.17	45.34	60.57	73.57
14	8.94	15.73	17.63	21.01	23.68	27.44	32	42.17	46.44	60.67	74.67
15	9.84	16.33	19.03	22.01	25.12	29.14	37.16	44.67	47.34	60.87	75.87
Total	262.54	436	519.9	591.1	680.9	763.3	906.11	1215	1273	1668	2089

Table C41: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 2mm (dia) Initial Bed Height = 9.0 cm Flowrate = 12.7 Lit/ min

Temperature = 29 C Voidage = 0.85

CATHODE SECTION	VOLTAGE (m V) → 50	100	150	200	250	300	350	400	450	500	550
1	11.38	18.05	21.76	26.07	30.29	37.53	47.49	55.2	54.2	72.2	87.43
2	10.62	17.1	21.56	24.97	29.49	37.43	47.49	55	53	72	87.23
3	10.62	16.5	21.06	24.47	29.29	35.93	46.39	53.8	51.9	70	85.23
4	10.38	16.9	21.06	24.47	28.49	34.93	45.49	52.9	51.9	69.7	84.93
5	16.98	31.6	38.85	45.38	57.38	72.04	94.07	118.9	101.3	136.3	171.33
6	37.87	61.01	72.89	84.88	94.36	117.7	156.76	187.9	167.2	224.4	285.42
7	36.79	59.54	72.85	84.88	94.36	116.4	155.56	185.2	165.6	222.2	283.22
8	36.11	59	72.3	81.58	91.86	113.7	152.66	184.8	164.6	220.8	281.82
9	35.67	58.01	71.34	80.58	91.26	113.6	153.06	183.9	164.6	220.8	281.82
10	27.8	42.6	53.35	57.67	58.47	72.51	101.78	114.8	116.3	143.4	184.62
11	9.76	16.5	19.26	25.97	26.39	32.73	42.89	50.3	47.2	63.8	79.53
12	9.58	16.3	19.06	23.07	26.09	32.73	42.89	50.3	47.2	63.8	79.03
13	9.58	16.3	19.06	22.87	26.19	32.93	42.59	50	47.4	64.2	78.43
14	9.78	16.5	19.26	23.27	26.39	32.73	42.59	50	48.5	64.1	79.53
15	8.58	12.5	14.93	17.3	17.46	22.06	28.43	30.53	32.93	42.3	52.03
Total	281.5	458.4	558.59	647.43	727.77	905	1200.1	1424	1314	1750	2201.6

Table C42: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 2mm (dia) Initial Bed Height = 9.0 cm Flowrate = 14.7 Lit/ min

Temperature = 29 C Voidage = 0.85

← V O L T A G E →
(m V)

CATHODE SECTION	50	100	150	200	250	300	350	400	450	500	550
1	11.64	19.62	24.73	27.9	35.09	42.37	52.02	63.54	67.24	85.9	106.8
2	10.88	18.67	24.53	26.8	34.29	42.27	52.02	63.34	66.04	85.7	106.6
3	10.88	18.07	24.03	26.3	34.09	40.77	50.92	62.14	64.94	83.7	104.6
4	10.64	18.47	24.03	26.3	33.29	39.77	50.02	61.24	64.94	83.4	104.3
5	10.64	18.47	24.03	26.3	33.29	39.77	50.12	61.34	64.94	83.4	104.3
6	37.61	65.99	83.47	90.9	112.26	135.8	173.58	220	218.1	277.9	361.6
7	36.53	64.52	83.43	90.9	112.26	134.5	172.38	217.3	216.5	275.7	359.4
8	35.85	63.98	82.88	87.6	109.76	131.8	169.48	216.9	215.5	274.3	358
9	35.41	62.99	81.92	86.6	109.16	131.7	169.88	216	215.5	274.3	358
10	34.14	62.28	81.72	84.6	105.26	127.7	167.08	212.8	216.6	263.5	347.2
11	10.12	18.17	22.33	27.9	31.29	37.67	47.52	58.74	60.34	77.6	99
12	9.94	17.97	22.13	25	30.99	37.67	47.52	58.74	60.34	77.6	98.5
13	9.94	17.97	22.13	24.8	31.09	37.87	47.22	58.44	60.54	78	97.9
14	10.14	18.17	22.33	25.2	31.29	37.67	47.22	58.44	61.64	77.9	99
15	11.14	19.07	23.93	26.2	31.99	39.37	49.22	60.94	62.54	78.3	100.3
Total	285.5	504.4	647.62	703.3	875.4	1057	1346.2	1690	1716	2177.2	2805.5

Table C43: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 2mm (dia) | Initial Bed Height = 12.0 cm | Flowrate = 5.8 Lit/ min

Temperature = 29 C | Voidage = 0.8

← V O L T A G E → (m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	11.34	19.05	22.66	26.64	33.86	40.94	48.82	60.74	57.24	75.2	93.1
2	11.34	18.1	22.46	25.54	33.06	40.84	48.82	60.54	56.04	75	92.9
3	10.58	17.5	21.96	25.04	32.86	39.34	47.72	59.34	54.94	73	90.9
4	10.34	17.9	21.96	25.04	32.06	38.34	46.82	58.44	54.94	72.7	90.6
5	10.34	17.9	21.96	25.04	32.06	38.34	46.92	58.54	54.94	72.7	90.6
6	36.21	63.51	74.99	85.65	107.14	129.9	160.58	208.5	177.9	234.9	306.6
7	35.13	62.04	74.95	85.66	107.14	128.6	159.38	205.9	176.3	232.7	304.4
8	34.45	61.5	74.4	82.36	104.64	125.9	156.48	205.5	175.3	231.3	303
9	34.01	60.51	73.44	81.36	104.04	125.8	156.88	204.6	175.3	231.3	303
10	30.84	57.9	71.34	77.46	98.24	119.9	152.18	199.5	174.5	218.6	290.3
11	9.72	17.5	20.16	26.54	29.96	36.14	44.22	55.84	50.24	66.8	85.2
12	9.54	17.3	19.96	23.64	29.66	36.14	44.22	55.84	50.24	66.8	84.7
13	9.54	17.3	19.96	23.44	29.76	36.34	43.92	55.54	50.44	67.2	84.1
14	9.74	17.5	20.16	23.84	29.96	36.14	43.92	55.54	51.54	67.1	85.2
15	10.74	18.4	21.76	24.84	30.66	37.84	45.92	58.04	52.44	67.5	86.5
Total	273.86	483.9	582.12	662.1	835.1	1010	1246.8	1602	1412	1852.8	2391.1

Table C44: Local Current of Individual Section for IncreasingApplied Voltage

Particle Size = 2mm (dia) Initial Bed Height = 12.0 cm Flowrate = 7.9 Lit/ min

Temperature = 29 C Voidage = 0.8

← V O L T A G E →
(m V)

Cathode Section	50	100	150	200	250	300	350	400	450	500	550
1	11.61	16.84	19.39	22.57	27.19	31.5	35.72	45.07	48.17	60.2	69.65
2	10.85	15.89	19.19	21.47	26.39	31.4	35.72	44.87	46.97	60	69.45
3	10.85	15.29	18.69	20.97	26.19	29.9	34.62	43.67	45.87	58	67.45
4	10.61	15.69	18.69	20:97	25.39	28.9	33.72	42.77	45.87	57.7	67.15
5	10.61	15.69	18.69	20.97	25.39	28.9	33.82	42.87	45.87	57.7	67.15
6	31.59	48.98	56.24	63.68	74.76	86.4	102.48	140.2	135.5	164.5	202.4
7	30.51	47.71	56.2	63.68	74.76	85.1	101.28	137.5	134.3	162.3	200.2
8	29.83	46.97	55.65	60.38	72.26	82.4	98.38	137.1	133.3	160.9	198.8
9	27.49	44.08	52.79	57.48	69.76	80.4	96.88	134.3	131.4	159	196.9
10	24.12	41.27	50.49	53.38	63.76	74.3	91.98	129	130.4	148.2	186.1
11	9.29	14.59	16.19	21.77	22.59	26	30.42	39.47	40.47	51	61.05
12	9.11	14.39	15.99	18.87	22.29	26	30.42	39:47	40.47	51	60.55
13	9.11	14.39	15.99	18.67	22.39	26.2	30.12	39.17	40.67	51.4	59.95
14	9.29	14.59	16.18	19.07	22.59	26	30.12	39.17	41.77	51.6	61.05
15	10.4	15.49	17.63	20.27	23.29	27.8	32.22	41.67	42.87	51.7	62.35
Total	245.27	381.9	448	504.2	599	691.2	817.9	1096	1104	1345.2	1630.2

Table C45: Local Current of Individual Section for IncreasingApplied Voltage

Particle Size = 2 mm (dia) | Initial Bed Height = 12.0 cm | Flowrate =8.9 Lit/ min

Temperature = 29 C | Voidage = 0.85

CATHODE SECTION	VOLTAGE (m V) → 50	100	150	200	250	300	350	400	450	500	550
1	10.84	16.58	19.46	23.07	27.82	31.9	35.82	46.77	50.67	62.3	71.82
2	10.08	15.63	19.26	21.97	27.02	31.8	35.82	46.57	49.47	62.1	71.62
3	10.08	15.03	18.76	21.47	26.82	30.3	34.72	45.37	48.37	60.1	69.62
4	9.84	15.43	18.76	21.47	26.02	29.3	33.82	44.47	48.37	59.8	69.32
5	9.84	15.43	18.76	21.47	26.02	29.3	33.92	44.57	48.37	59.8	69.32
6	35.11	54.53	63.09	72.28	83.88	94.6	109.48	153.6	152.5	184.2	222.4
7	34.03	53.06	63.05	72.28	83.88	93.3	108.28	150.9	150.9	182	220.2
8	33.35	52.52	62.5	68.98	81.38	90.6	105.38	150.5	149.9	180.6	218.8
9	32.91	51.53	61.54	67.98	80.78	90.5	105.78	149.6	149.9	180.6	218.8
10	33.6	42.44	61.34	65.98	76.88	86.5	102.98	146.4	151	169.8	208
11	9.82	14.79	16.39	21.97	22.79	29.2	33.62	42.67	43.67	54.2	61.8
12	9.01	14.29	15.89	18.77	22.19	25.9	30.32	39.37	40.37	50.9	60.45
13	9.01	14.29	15.89	18.57	22.29	26.1	30.02	39.07	40.57	51.3	59.85
14	9.19	14.49	16.08	18.97	22.49	25.9	30.02	39.07	41.67	51.5	60.95
15	11.3	16.39	18.53	21.17	24.19	28.7	33.12	42.57	43.77	52.6	63.25
Total	268.01	406.4	489.3	556.4	654.45	743.9	863.1	1181	1209	1461.8	1746.2

Table C46: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 2mm (dia) Initial Bed Height = 12.0 cm Flowrate = 10.5Lit/ min

Temperature = 29 C Voidage = 0.85

← V O L T A G E (m V) →

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	10.84	16.58	19.46	23.07	27.82	31.9	35.82	46.77	50.67	62.3	71.82
2	10.08	15.63	19.26	21.97	27.02	31.8	35.82	46.57	49.47	62.1	71.62
3	10.08	15.03	18.76	21.47	26.82	30.3	34.72	45.37	48.37	60.1	69.62
4	9.84	15.43	18.76	21.47	26.02	29.3	33.82	44.47	48.37	59.8	69.32
5	9.84	15.43	18.76	21.47	26.02	29.3	33.92	44.57	48.37	59.8	69.32
6	35.11	54.53	63.09	72.28	83.88	94.6	109.48	153.6	152.5	184.2	222.4
7	34.03	53.06	63.05	72.28	83.88	93.3	108.28	150.9	150.9	182	220.2
8	33.35	52.52	62.5	68.98	81.38	90.6	105.38	150.5	149.9	180.6	218.8
9	32.91	51.53	61.54	67.98	80.78	90.5	105.78	149.6	149.9	180.6	218.8
10	33.6	42.44	61.34	65.98	76.88	86.5	102.98	146.4	151	169.8	208
11	9.82	14.79	16.39	21.97	22.79	29.2	33.62	42.67	43.67	54.2	61.8
12	9.01	14.29	15.89	18.77	22.19	25.9	30.32	39.37	40.37	50.9	60.45
13	9.01	14.29	15.89	18.57	22.29	26.1	30.02	39.07	40.57	51.3	59.85
14	9.19	14.49	16.08	18.97	22.49	25.9	30.02	39.07	41.67	51.5	60.95
15	11.3	16.39	18.53	21.17	24.19	28.7	33.12	42.57	43.77	52.6	63.25
Total	268.01	406.4	489.3	556.4	654.45	743.9	863.1	1181	1209	1461.8	1746.2

Table C47: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 2mm (dia) | **Initial Bed Height = 12.0 cm** | Flowrate =11.4 Lit/ min

Temperature = 29 C | Voidage = 0.8

← V O L T A G E →
(m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	12.71	18.28	21.13	24.47	29.39	33.7	40.92	49.67	54.44	70.87	84.87
2	11.95	17.33	20.93	23.37	28.59	33.6	40.92	49.47	53.24	70.67	84.67
3	11.95	16.73	20.43	22.87	28.39	32.1	39.82	48.27	52.14	68.67	82.67
4	11.71	17.13	20.43	22.87	27.59	31.1	38.92	47.37	52.14	68.37	82.37
5	11.71	17.13	20.43	22.87	27.59	31.1	39.02	47.47	52.14	68.37	82.37
6	41.19	59.93	68.37	76.48	88.76	100.4	128.48	163.8	166.2	217.24	273.18
7	40.11	58.46	68.33	76.48	88.76	99.08	127.28	161.1	164.6	215.04	270.98
8	39.43	57.92	67.78	73.18	86.26	96.38	124.38	160.7	163.6	213.64	269.58
9	38.99	56.93	66.82	72.18	85.66	96.28	124.78	159.8	163.6	213.64	269.58
10	37.72	56.22	66.62	70.18	81.76	92.28	121.98	156.6	164.7	202.84	258.78
11	10.79	16.43	18.33	24.07	25.19	28.6	36.02	44.47	47.14	62.17	76.67
12	10.61	16.23	18.13	21.17	24.89	28.6	36.02	44.47	47.14	62.17	76.17
13	10.61	16.23	18.13	20.97	24.99	28.8	35.72	44.17	47.34	62.17	75.57
14	10.11	15.73	17.63	20.47	24.49	27.9	35.12	43.47	47.74	61.77	75.97
15	13.71	19.53	21.61	23.67	27.79	32.4	39.62	48.57	51.34	64.57	79.77
Total	313.3	460.2	535.1	595.3	700.1	792.3	1009	1269	1327	1722.2	2143.2

Table C48: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 2mm (dia) Initial Bed Height = 12.0 cm Flowrate = 12.7 Lit/ min

Temperature = 29 C Voidage = 0.8

VOLTAGE (m V)

CATHODE SECTION	50	100	150	200	250	300	350	400	450	500	550
1	13.52	19.78	22.93	26.61	31.35	35.04	39.7	50.17	54.94	71.37	85.37
2	12.56	18.83	22.73	25.51	30.35	34.94	39.7	49.97	53.74	71.17	85.17
3	12.56	18.23	22.23	25.01	30.15	33.44	38.6	48.77	52.64	69.17	83.17
4	12.32	18.63	22.23	25.01	29.35	32.44	37.7	47.87	52.64	68.87	82.87
5	12.32	18.63	22.23	25.01	29.35	32.44	37.8	47.97	52.64	68.87	82.87
6	41.83	64.13	73.77	83.24	94	104	121.77	164	166.4	217.28	273.38
7	40.75	62.66	73.73	83.24	94	102.7	120.57	161.3	164.8	215.08	271.18
8	40.07	62.12	73.16	79.94	91.5	99.98	117.67	160.9	163.8	213.68	269.78
9	39.63	61.13	72.22	78.94	89.68	99.88	118.07	160	163.8	213.68	269.78
10	38.36	60.42	72.02	76.94	87	95.88	115.27	156.8	164.9	202.88	258.98
11	11.1	17.63	19.83	25.91	26.65	29.64	34.5	44.67	47.34	62.37	76.87
12	10.92	17.43	19.63	23.01	26.35	29.64	34.5	44.67	47.34	62.37	76.37
13	10.92	17.43	19.63	22.81	25.47	29.84	34.2	44.37	47.54	62.77	75.77
14	10.44	17.23	19.13	22.51	25.18	28.94	33.5	43.67	47.94	62.17	76.17
15	13.04	19.53	22.23	25.21	28.32	32.34	40.36	47.87	50.54	64.07	79.07
Total	320.34	493.8	577.7	648.9	738.7	821.1	963.91	1273	1331	1725.8	2146.8

Table C49: Local Current of Individual Section for Increasing VApplied Voltage

Particle Size = 2 mm (dia) Initial Bed Height = 12.0 cm Flowrate = 14.6Lit/ min

Temperature = 29 C Voidage = 0.8

← V O L T A G E (m V) →

CATHODE SECTION ↓		50	100	150	200	250	300	350	400	450	500	550
	1	13.88	20.55	24.26	28.57	32.79	40.03	49.99	57.7	56.7	74.7	89.93
	2	13.12	19.6	24.06	27.47	31.99	39.93	49.99	57.5	55.5	74.5	89.73
	3	13.12	19	23.56	26.97	31.79	38.43	48.89	56.3	54.4	72.5	87.73
	4	12.88	19.4	23.56	26.97	30.99	37.43	47.99	55.4	54.4	72.2	87.43
	5	12.88	19.4	23.56	26.97	30.99	37.43	48.09	55.5	54.4	72.2	87.43
	6	44.97	68.11	79.99	91.98	101.46	124.8	163.86	195	174.3	231.5	292.52
	7	43.89	66.64	79.95	91.98	101.46	123.5	162.66	192.3	172.7	229.3	290.32
	8	43.21	66.1	79.4	88.68	98.96	120.8	159.76	191.9	171.7	227.9	288.92
	9	42.77	65.11	78.44	87.68	98.36	120.7	160.16	191	171.7	227.9	288.92
	10	41.5	64.4	78.24	85.68	94.46	116.7	157.36	187.8	172.8	217.1	278.12
	11	12.26	19	21.76	28.47	28.89	35.23	45.39	52.8	49.7	66.3	82.03
	12	12.08	18.8	21.56	25.57	28.59	35.23	45.39	52.8	49.7	66.3	81.53
	13	12.08	18.8	21.56	25.37	28.69	35.43	45.09	52.5	49.9	66.7	80.93
	14	12.28	19	21.76	25.77	28.89	35.23	45.09	52.5	51	66.6	82.03
	15	13.28	19.9	23.36	26.77	29.59	36.93	47.09	55	51.9	67	83.33
Total		344.2	523.8	625.02	714.9	797.9	977.9	1276.8	1506	1391	1832.7	2290.9

Total

Table C50: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 2mm (dia) Initial Bed Height = 15.0 cm Flowrate = 5.8 Lit/ min

Temperature = 29 C Voidage = 0.75

← V O L T A G E →
(m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	8.64	16.35	19.96	23.94	31.16	38.24	46.12	58.04	54.54	72.5	90.4
2	8.64	15.4	19.76	22.84	30.36	38.14	46.12	57.84	53.34	72.3	90.2
3	7.88	14.8	19.26	22.34	30.16	36.64	45.02	56.64	52.24	70.3	88.2
4	7.64	15.2	19.26	22.34	29.36	35.64	44.12	55.74	52.24	70	87.9
5	7.64	15.2	19.26	22.34	29.36	35.64	44.22	55.84	52.24	70	87.9
6	31.51	58.81	70.29	80.96	102.44	125.2	155.88	203.9	173.2	230.2	301.9
7	30.43	57.34	70.25	80.96	102.44	123.9	154.68	201.2	171.6	228	299.7
8	29.75	56.8	69.7	77.66	99.94	121.2	151.78	200.8	170.6	226.6	298.3
9	29.31	55.81	68.74	76.66	99.34	121.1	152.18	199.9	170.6	226.6	298.3
10	26.14	53.2	66.64	72.76	93.54	115.2	147.48	194.8	169.8	213.9	285.6
11	8.02	15.8	18.46	24.84	28.26	34.44	42.52	54.14	48.54	65.1	83.5
12	7.84	15.6	18.26	21.94	27.96	34.44	42.52	54.14	48.54	65.1	83
13	7.84	15.6	18.26	21.74	28.06	34.64	42.22	53.84	48.74	65.5	82.4
14	8.04	15.8	18.46	22.14	28.26	34.44	42.22	53.84	49.84	65.4	83.5
15	9.04	16.7	20.06	23.14	28.96	36.14	44.22	56.34	50.74	65.8	84.8
Total	228.36	438.4	536.62	616.6	789.6	964.8	1201.3	1557	1367	1807.3	2345.6

Table C51: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 2mm (dia) Initial Bed Height = 15.0 cm Flowrate =7.9 Lit/ min

Temperature = 29 C Voidage = 0.75

← V O L T A G E → (m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	8.91	14.14	16.69	19.87	24.49	28.8	33.02	42.37	45.47	57.5	66.95
2	8.15	13.19	16.49	18.77	23.69	28.7	33.02	42.17	44.27	57.3	66.75
3	8.15	12.59	15.99	18.27	23.49	27.2	31.92	40.97	43.17	55.3	64.75
4	7.91	12.99	15.99	18.27	22.69	26.2	31.02	40.07	43.17	55	64.45
5	7.91	12.99	15.99	18.27	22.69	26.2	31.12	40.17	43.17	55	64.45
6	25.89	43.28	50.54	57.98	69.06	80.7	96.78	134.5	130.2	158.8	196.7
7	24.81	42.01	50.5	57.93	69.06	79.4	95.58	131.8	128.6	156.6	194.5
8	24.13	41.27	49.95	54.68	66.56	76.7	92.68	131.4	127.6	155.2	193.1
9	21.79	38.38	47.09	51.78	64.06	74.7	91.18	128.6	125.7	153.3	191.2
10	18.42	35.57	44.79	47.68	58.06	68.6	86.28	123.3	124.7	142.5	180.4
11	7.49	12.79	14.39	19.97	20.79	24.2	28.62	37.67	38.67	49.2	59.25
12	7.31	12.59	14.19	17.07	20.49	24.2	28.62	37.67	38.67	49.2	58.75
13	7.31	12.59	14.19	16.87	20.59	24.4	28.32	37.37	38.87	49.6	58.15
14	7.49	12.79	14.38	17.27	20.79	24.2	28.32	37.37	39.97	49.8	59.25
15	8.6	13.69	15.83	18.47	21.49	26	30.42	39.87	41.07	49.9	60.55
Total	194.27	330.9	397	453.2	548	640.2	766.9	1045	1053	1294.2	1579.2

Table C52: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 2mm (dia) Initial Bed Height = 15.0 cm Flowrate = 8.7 Lit/ min

Temperature = 29 C Voidage = 0.75

← V O L T A G E →
(m A)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	8.54	14.28	17.16	20.77	25.52	29.6	33.52	44.47	48.37	60	69.52
2	7.78	13.33	16.96	19.67	24.72	29.5	33.52	44.27	47.17	59.8	69.32
3	7.78	12.73	16.46	19.17	24.52	28	32.42	43.07	46.07	57.8	67.32
4	7.54	13.13	16.46	19.17	23.72	27	31.52	42.17	46.07	57.5	67.02
5	7.54	13.13	16.46	19.17	23.72	27	31.62	42.27	46.07	57.5	67.02
6	29.71	49.13	57.69	66.88	78.48	89.2	104.08	148.2	147.1	178.8	217
7	28.63	47.66	57.65	66.88	78.48	87.9	102.88	145.5	145.5	176.6	214.8
8	27.95	47.12	57.1	63.58	75.98	85.2	99.98	145.1	144.5	175.2	213.4
9	27.51	46.13	56.14	62.58	75.38	85.1	100.38	144.2	144.5	175.2	213.4
10	28.2	37.04	55.94	60.58	71.48	81.1	97.58	141	145.6	164.4	202.6
11	8.42	13.39	14.99	20.57	21.39	27.8	32.22	41.27	42.27	52.8	60.4
12	7.61	12.89	14.49	17.37	20.79	24.5	28.92	37.97	38.97	49.5	59.05
13	7.61	12.89	14.49	17.17	20.89	24.7	28.62	37.67	39.17	49.9	58.45
14	7.79	13.09	14.68	17.57	21.09	24.5	28.62	37.67	40.27	50.1	59.55
15	9.9	14.99	17.13	19.77	22.79	27.3	31.72	41.17	42.37	51.2	61.85
Total	222.51	360.9	443.8	510.9	608.95	698.4	817.6	1136	1164	1416.3	1700.7

Table C53: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 2mm (dia)   Initial Bed Height = 15.0 cm   Flowrate = 10.5 Lit/ min

Temperature = 29 C   Voidage = 0.75

← V O L T A G E →
(m A)

Cathode Section ↓	50	100	150	200	250	300	350	400	450	500	550
1	10.21	15.78	18.63	21.97	26.89	31.2	38.42	47.17	51.94	68.37	82.37
2	9.45	14.83	18.43	20.87	26.09	31.1	38.42	46.97	50.74	68.17	82.17
3	9.45	14.23	17.93	20.37	25.89	29.6	37.32	45.77	49.64	66.17	80.17
4	9.21	14.63	17.93	20.37	25.09	28.6	36.42	44.87	49.64	65.87	79.87
5	9.21	14.63	17.93	20.37	25.09	28.6	36.52	44.97	49.64	65.87	79.87
6	36.69	55.43	63.87	71.98	84.26	95.88	123.98	159.3	161.7	212.74	268.68
7	35.61	53.96	63.83	71.98	84.26	94.58	122.78	156.6	160.1	210.54	266.48
8	34.93	53.42	63.28	68.68	81.76	91.88	119.88	156.2	159.1	209.14	265.08
9	34.49	52.43	62.32	67.68	81.16	91.78	120.28	155.3	159.1	209.14	265.08
10	33.22	51.72	62.12	65.68	77.26	87.78	117.48	152.1	160.2	198.34	254.28
11	8.29	13.93	15.83	21.57	22.69	26.1	33.52	41.97	44.64	59.67	74.17
12	8.11	13.73	15.63	18.67	22.39	26.1	33.52	41.97	44.64	59.67	73.67
13	8.11	13.73	15.63	18.47	22.49	26.3	33.22	41.67	44.84	59.67	73.07
14	7.61	13.23	15.13	17.97	21.99	25.4	32.62	40.97	45.24	59.27	73.47
15	11.21	17.03	19.11	21.17	25.29	29.9	37.12	46.07	48.84	62.07	77.27
Total	265.8	412.7	487.6	547.8	652.6	744.8	961.5	1222	1280	1674.7	2095.7

Table C54: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 2mm (dia) | Initial Bed Height = 15.0 cm | Flowrate = 11.4 Lit/ min

Temperature = 29 C | Voidage = 0.75

VOLTAGE (m V)

CATHODE SECTION	50	100	150	200	250	300	350	400	450	500	550
1	10.92	17.18	20.33	24.01	28.75	32.44	37.1	47.57	52.34	68.77	82.77
2	9.96	16.23	20.13	22.91	27.75	32.34	37.1	47.37	51.14	68.57	82.57
3	9.96	15.63	19.63	22.41	27.55	30.84	36	46.17	50.04	66.57	80.57
4	9.72	16.03	19.63	22.41	26.75	29.84	35.1	45.27	50.04	66.27	80.27
5	9.72	16.03	19.63	22.41	26.75	29.84	35.2	45.37	50.04	66.27	80.27
6	39.23	61.53	71.17	80.64	91.4	101.4	119.17	161.4	163.8	214.68	270.78
7	38.15	60.06	71.13	80.64	91.4	100.1	117.97	158.7	162.2	212.48	268.58
8	37.47	59.52	70.56	77.34	88.9	97.38	115.07	158.3	161.2	211.08	267.18
9	37.03	58.53	69.62	76.34	87.08	97.28	115.47	157.4	161.2	211.08	267.18
10	35.76	57.82	69.42	74.34	84.4	93.28	112.67	154.2	162.3	200.28	256.38
11	8.5	15.03	17.23	23.31	24.05	27.04	31.9	42.07	44.74	59.77	74.27
12	8.32	14.83	17.03	20.41	23.75	27.04	31.9	42.07	44.74	59.77	73.77
13	8.32	14.83	17.03	20.21	22.87	27.24	31.6	41.77	44.94	60.17	73.17
14	7.84	14.63	16.53	19.91	22.58	26.34	30.9	41.07	45.34	59.57	73.57
15	10.44	16.93	19.63	22.61	25.72	29.74	37.76	45.27	47.94	61.47	76.47
Total	281.34	454.8	538.7	609.9	699.7	782.1	924.91	1234	1292	1686.8	2107.8

Table C55: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 2 mm (dia) | Initial Bed Height = 15.0 cm | Flowrate = 12.7 Lit/ min

Temperature = 29 C | Voidage = 0.75

← V O L T A G E →
(m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	11.28	17.95	21.66	25.97	30.19	37.43	47.39	55.1	54.1	72.1	87.33
2	10.52	17	21.46	24.87	29.39	37.33	47.39	54.9	52.9	71.9	87.13
3	10.52	16.4	20.96	24.37	29.19	35.83	46.29	53.7	51.8	69.9	85.13
4	10.28	16.8	20.96	24.37	28.39	34.83	45.39	52.8	51.8	69.6	84.83
5	10.28	16.8	20.96	24.37	28.39	34.83	45.49	52.9	51.8	69.6	84.83
6	38.37	61.51	73.39	85.38	94.86	118.2	157.26	188.4	167.7	224.9	285.92
7	37.29	60.04	73.35	85.38	94.86	116.9	156.06	185.7	166.1	222.7	283.72
8	36.61	59.5	72.8	82.08	92.36	114.2	153.16	185.3	165.1	221.3	282.32
9	36.17	58.51	71.84	81.08	91.76	114.1	153.56	184.4	165.1	221.3	282.32
10	34.9	57.8	71.64	79.08	87.86	110.1	150.76	181.2	166.2	210.5	271.52
11	9.66	16.4	19.16	25.87	26.29	32.63	42.79	50.2	47.1	63.7	79.43
12	9.48	16.2	18.96	22.97	25.99	32.63	42.79	50.2	47.1	63.7	78.93
13	9.48	16.2	18.96	22.77	26.09	32.83	42.49	49.9	47.3	64.1	78.33
14	9.68	16.4	19.16	23.17	26.29	32.63	42.49	49.9	48.4	64	79.43
15	10.68	17.3	20.76	24.17	26.99	34.33	44.49	52.4	49.3	64.4	80.73
Total	285.2	464.8	566.02	655.9	733.9	918.9	1217.8	1447	1332	1773.7	2231.9

Table C56: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 2 mm (dia) **Initial Bed Height = 15.0 cm** Flowrate = 14.6Lit/min

Temperature = 29 C Voidage = 0.75

← V O L T A G E →
(m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	8.98	15.65	19.36	23.67	27.89	35.13	45.09	52.8	51.8	69.8	85.03
2	8.22	14.7	19.16	22.57	27.09	35.03	45.09	52.6	50.6	69.6	84.83
3	8.22	14.1	18.66	22.07	26.89	33.53	43.99	51.4	49.5	67.6	82.83
4	7.98	14.5	18.66	22.07	26.09	32.53	43.09	50.5	49.5	67.3	82.53
5	7.98	14.5	18.66	22.07	26.09	32.53	43.19	50.6	49.5	67.3	82.53
6	33.07	56.21	68.09	80.08	89.56	112.9	151.96	183.1	162.4	219.6	280.62
7	31.99	54.74	68.05	80.08	89.56	111.6	150.76	180.4	160.8	217.4	278.42
8	31.31	54.2	67.5	76.78	87.06	108.9	147.86	180	159.8	216	277.02
9	30.87	53.21	66.54	75.78	86.46	108.8	148.26	179.1	159.8	216	277.02
10	29.6	52.5	66.34	73.78	82.56	104.8	145.46	175.9	160.9	205.2	266.22
11	7.36	14.1	16.86	23.57	23.99	30.33	40.49	47.9	44.8	61.4	77.13
12	7.18	13.9	16.66	20.67	23.69	30.33	40.49	47.9	44.8	61.4	76.63
13	7.18	13.9	16.66	20.47	23.79	30.53	40.19	47.6	45	61.8	76.03
14	7.38	14.1	16.86	20.87	23.99	30.33	40.19	47.6	46.1	61.7	77.13
15	8.38	15	18.46	21.87	24.69	32.03	42.19	50.1	47	62.1	78.43
Total	235.7	415.3	516.52	606.4	689.4	869.4	1168.3	1398	1282	1724.2	2182.4

Table C57: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 6.0 cm Flowrate = 5.8 Lit/ min

Temperature = 29 C Voidage = 0.9

SECTION	VOLTAGE (m V) 50	100	150	200	250	300	350	400	450	500	550
1	4.34	6.65	8.2	10.1	12	13.6	13.9	14.2	21.7	28.2	32.9
2	3.58	5.7	8	9	11.2	13.5	13.9	14	20.5	28	32.7
3	3.58	5.1	7.5	8.5	11	12	12.8	12.8	19.4	26	30.7
4	3.34	5.5	7.5	8.5	10.2	11	11.9	11.9	19.4	25.7	30.4
5	3.34	5.5	7.5	8.5	10.2	11	12	12	19.4	25.7	30.4
6	11.51	17.21	20.45	22.8	23	23.8	24.2	25.7	39	50.2	69.1
7	10.43	15.74	20.41	22.8	23	22.5	23	23	37.4	48	66.9
8	9.75	15.2	19.86	19.5	20.5	19.8	20.1	22.6	36.4	46.6	65.5
9	9.31	14.21	18.9	18.5	19.9	19.7	20.5	21.7	36.4	46.6	65.5
10	8.04	13.5	18.7	16.5	16	15.7	17.7	18.5	37.5	35.8	54.7
11	3.22	5.6	6.2	10.5	8.6	9.3	9.8	9.8	15.2	20.3	25.5
12	3.04	5.4	6	7.6	8.3	9.3	9.8	9.8	15.2	20.3	25
13	3.04	5.4	6	7.4	8.4	9.5	9.5	9.5	15.4	20.7	24.4
14	3.24	5.6	6.2	7.8	8.6	9.3	9.5	9.5	16.5	20.6	25.5
15	4.24	6.5	7.8	8.8	9.3	11	11.5	12	17.4	21	26.8
Total	84	132.8	169.22	186.8	200.2	211	220.1	227	366.8	463.7	606

Table C58: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 6.0 cm Flowrate = 7.9 Lit/ min

Temperature = 29 C Voidage = 0.9

← V O L T A G E → (m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	4.51	7.04	8.56	10.7	12.66	14.23	14.66	18.2	26.8	33.1	35.95
2	3.75	6.09	8.36	9.6	11.86	14.13	14.66	18	25.6	32.9	35.75
3	3.75	5.49	7.86	9.1	11.66	12.63	13.56	16.8	24.5	30.9	33.75
4	3.51	5.89	7.86	9.1	10.86	11.63	12.66	15.9	24.5	30.6	33.45
5	3.51	5.89	7.86	9.1	10.86	11.63	12.76	16	24.5	30.6	33.45
6	12.19	18.78	21.92	25.2	25.64	26.32	27.24	41.7	59.4	69.8	81.3
7	11.11	17.51	21.88	25.2	25.64	25.02	26.04	39	57.8	67.6	79.1
8	10.43	16.77	21.33	21.9	23.14	22.32	23.14	38.6	56.8	66.2	77.7
9	9.99	15.78	20.37	20.9	22.54	22.22	23.54	37.7	56.8	66.2	77.7
10	8.72	15.07	20.17	18.9	18.64	18.22	20.74	34.5	57.9	55.4	66.9
11	3.39	5.99	6.56	11.1	9.26	9.93	10.56	13.8	20.3	25.1	28.55
12	3.21	5.79	6.36	8.2	8.96	9.93	10.56	13.8	20.3	25.1	28.05
13	3.21	5.79	6.36	8	9.06	10.13	10.26	13.5	20.5	25.5	27.45
14	3.39	5.99	6.55	8.4	9.26	9.93	10.26	13.5	21.6	25.7	28.55
15	4.5	6.89	8	9.6	9.96	11.73	12.36	16	22.7	25.8	29.85
Total	89.17	144.8	180	205	220	230	243	347	520	610.5	697.5

Table C59: Local Current of Individual Section for increasing Applied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 6.0 cm Flowrate = 8.9 Lit/ min

Temperature = 29 C Voidage = 0.9

Cathode Section	VOLTAGE (m V) → 50	100	150	200	250	300	350	400	450	500	550
1	4.34	7.38	9.23	11.8	13.89	15.23	15.36	20.5	29.9	35.8	38.72
2	3.58	6.43	9.03	10.7	13.09	15.13	15.36	20.3	28.7	35.6	38.52
3	3.58	5.83	8.53	10.2	12.89	13.63	14.26	19.1	27.6	33.6	36.52
4	3.34	6.23	8.53	10.2	12.09	12.63	13.36	18.2	27.6	33.3	36.22
5	3.34	6.23	8.53	10.2	12.09	12.63	13.46	18.3	27.6	33.3	36.22
6	11.51	20.13	24.57	29.6	30.56	30.32	30.04	50.9	71.8	80.6	92.4
7	10.43	18.66	24.53	29.6	30.56	29.02	28.84	48.2	70.2	78.4	90.2
8	9.75	18.12	23.98	26.3	28.06	26.32	25.94	47.8	69.2	77	88.8
9	9.31	17.13	23.02	25.3	27.46	26.22	26.34	46.9	69.2	77	88.8
10	8.04	16.42	22.82	23.3	23.56	22.22	23.54	43.7	70.3	66.2	78
11	3.22	6.33	7.23	12.2	10.49	10.93	11.26	16.1	23.4	27.9	31.32
12	3.04	6.13	7.03	9.3	10.15	10.53	11.26	16.1	23.4	27.9	30.82
13	3.04	6.13	7.03	9.1	10.29	11.13	10.96	15.8	23.6	28.3	30.22
14	3.24	6.63	7.11	9.7	10.49	11.03	11.06	15.8	24.7	28.2	31.32
15	4.24	7.23	8.83	10.5	11.29	12.63	12.96	18.3	25.8	28.9	32.42
Total	84	155	200	238	257	260	264	416	613	692	780.5

Table C60: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 6.0 cm Flowrate = 10.5 Lit/ min

Temperature = 29 C Voidage = 0.9

CATHODE SECTION	VOLTAGE (m V) → 50	100	150	200	250	300	350	400	450	500	550
1	5.91	8.78	10.6	12.9	15.16	16.73	20.16	23.1	33.37	44.07	51.47
2	5.15	7.83	10.4	11.8	14.36	16.63	20.16	22.9	32.17	43.87	51.27
3	5.15	7.23	9.9	11.3	14.16	15.13	19.06	21.7	31.07	41.87	49.27
4	4.91	7.63	9.9	11.3	13.36	14.13	18.16	20.8	31.07	41.57	48.97
5	4.91	7.63	9.9	11.3	13.36	14.13	18.26	20.9	31.07	41.57	48.97
6	17.79	25.73	30.05	34	35.64	36.3	49.24	61.3	85.68	113.84	143.38
7	16.71	24.26	30.01	34	35.64	35	48.04	58.6	84.08	111.64	141.18
8	16.03	23.72	29.46	30.7	33.14	32.3	45.14	58.2	83.08	110.24	139.78
9	15.59	22.73	28.5	29.7	32.54	32.2	45.54	57.3	83.08	110.24	139.78
10	14.32	22.02	28.3	27.7	28.64	28.2	42.74	54.1	84.18	99.44	128.98
11	4.79	7.73	8.6	13.3	11.76	12.43	16.06	18.7	26.87	36.17	44.07
12	4.61	7.53	8.4	10.4	11.46	12.43	16.06	18.7	26.87	36.17	43.57
13	4.61	7.53	8.4	10.2	11.56	12.63	15.76	18.4	27.07	36.17	42.97
14	4.81	7.73	8.6	10.4	11.76	12.43	15.86	18.4	28.17	36.47	44.07
15	5.81	8.93	9.98	11	12.46	14.33	17.76	20.9	29.17	36.67	45.27
Total	131.1	197	241	270	295	305	408	494	717	940	1163

Table C61: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 6.0 cm Flowrate = 11.4 Lit/ min

Temperature = 29 C Voidage = 0.9

		VOLTAGE (m V)										
		50	100	150	200	250	300	350	400	450	500	550
CATHODE SECTION	1	6.22	9.78	11.9	14.54	16.62	17.57	18.44	23.1	33.37	44.07	51.47
	2	5.26	8.83	11.7	13.44	15.62	17.47	18.44	22.9	32.17	43.87	51.27
	3	5.26	8.23	11.2	12.94	15.42	15.97	17.34	21.7	31.07	41.87	49.27
	4	5.02	8.63	11.2	12.94	14.62	14.97	16.44	20.8	31.07	41.57	48.97
	5	5.02	8.63	11.2	12.94	14.62	14.97	16.54	20.9	31.07	41.57	48.97
	6	18.23	29.73	35.25	40.56	40.68	39.7	42.33	61.3	85.7	113.68	143.38
	7	17.15	28.26	35.21	40.56	40.68	38.4	41.13	58.6	84.1	111.48	141.18
	8	16.47	27.72	34.64	37.26	38.18	35.7	38.23	58.2	83.1	110.08	139.78
	9	16.03	26.73	33.7	36.26	36.36	35.6	38.63	57.3	83.1	110.08	139.78
	10	14.76	26.02	33.5	34.26	33.68	31.6	35.83	54.1	84.2	99.28	128.98
	11	4.9	8.73	9.9	14.94	13.02	13.27	14.34	18.7	26.87	36.17	44.07
	12	4.72	8.53	9.7	12.04	12.72	13.27	14.34	18.7	26.87	36.17	43.57
	13	4.72	8.53	9.7	11.84	11.84	13.47	14.04	18.4	27.07	36.57	42.97
	14	4.94	9.03	9.9	12.24	12.25	13.27	14.04	18.4	28.17	36.67	44.07
	15	5.84	9.63	11.3	13.24	13.69	14.97	19.2	20.9	29.07	36.87	45.27
Total		134.54	227	280	320	330	330.2	359.31	494	717	940	1163

Table C62: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 6.0 cm Flowrate = 12.7 Lit/ min

Temperature = 29 C Voidage = 0.9

VOLTAGE (m V)

CATHODE SECTION	50	100	150	200	250	300	350	400	450	500	550
1	6.58	10.55	13.23	16.5	18.06	22.56	28.73	30.63	35.13	47.4	56.03
2	5.82	9.6	13.03	15.4	17.26	22.46	28.73	30.43	33.93	47.2	55.83
3	5.82	9	12.53	14.9	17.06	20.96	27.63	29.23	32.83	45.2	53.83
4	5.58	9.4	12.53	14.9	16.26	19.96	26.73	28.33	32.83	44.9	53.53
5	5.58	9.4	12.53	14.9	16.26	19.96	26.83	28.43	32.83	44.9	53.53
6	20.47	32.81	40.57	48.4	47.24	59.64	83.52	91.42	92.72	127	161.62
7	19.39	31.34	40.53	48.4	47.24	58.34	82.32	88.72	91.12	124.8	159.42
8	18.71	30.8	39.98	45.1	44.74	55.64	79.42	88.32	90.12	123.4	158.02
9	18.27	29.81	39.02	44.1	44.14	56.54	79.82	87.42	90.12	123.4	158.02
10	17	29.1	38.82	42.1	40.24	51.54	77.02	84.22	91.22	112.6	147.22
11	5.46	9.5	11.23	16.9	14.66	18.26	24.63	26.23	28.63	39.5	48.63
12	5.28	9.3	11.03	14	14.36	18.26	24.63	26.23	28.63	39.5	48.13
13	5.28	9.3	11.03	13.8	14.46	18.46	24.33	25.93	28.83	39.9	47.53
14	5.48	9.5	11.23	14.2	14.66	18.26	24.33	25.93	29.93	39.8	48.63
15	6.48	10.4	12.83	15.2	15.36	19.96	26.33	28.43	30.83	40.2	49.93
Total	151.2	249.8	320.12	378.8	382	479.8	665	719.9	769.7	1039.7	1299.9

Table C63: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 6.0 cm Flowrate = 14.6 Lit/ min

Temperature = 29 C Voidage = 0.9

← V O L T A G E (m V) →

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	7.14	12.42	16.5	18.63	23.16	27.7	33.56	39.27	48.47	61.4	75.7
2	6.38	11.47	16.3	17.53	22.36	27.6	33.56	39.07	47.27	61.2	75.5
3	6.38	10.87	15.8	17.03	22.16	26.1	32.46	37.87	46.17	59.2	73.5
4	6.14	11.27	15.8	17.03	21.36	25.1	31.56	36.97	46.17	58.9	73.2
5	6.14	11.27	15.8	17.03	21.36	25.1	31.66	37.07	46.17	58.9	73.2
6	22.71	40.29	53.65	56.92	67.64	80.2	102.84	126	146.1	183	240.3
7	21.63	38.82	53.61	56.92	67.64	78.9	101.64	123.3	144.5	180.8	238.1
8	20.95	38.28	53.06	53.62	65.14	76.2	98.74	122.9	143.5	179.4	236.7
9	20.51	37.29	52.1	52.62	64.54	76.1	99.14	122	143.5	179.4	236.7
10	19.24	36.58	51.9	50.62	60.64	72.1	96.34	118.8	144.6	168.6	225.9
11	6.02	11.37	14.5	19.03	19.76	23.4	29.46	34.87	41.97	53.5	68.3
12	5.84	11.17	14.3	16.13	19.46	23.4	29.46	34.87	41.97	53.5	67.8
13	5.84	11.17	14.3	15.93	19.56	23.6	29.16	34.57	42.17	53.9	67.2
14	6.04	11.37	14.5	16.33	19.76	23.4	29.16	34.57	43.27	53.8	68.3
15	7.04	12.27	16.1	17.33	20.46	25.1	31.16	37.07	44.17	54.2	69.6
Total	168	305.9	418.22	442.7	535	634	809.9	979.1	1170	1459.7	1890

Table C64: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 9.0 cm Flowrate = 5.8 Lit/ min

Temperature = 29 C Voidage = 0.85

		VOLTAGE (m V) →										
		50	100	150	200	250	300	350	400	450	500	550
CATHODE SECTION ↓	1	6.54	11.55	14.13	17.07	21.63	25.97	30.06	36.17	38.17	50.4	61.7
	2	5.78	10.6	13.93	15.97	20.83	25.87	30.06	35.97	36.97	50.2	61.5
	3	5.78	10	13.43	15.47	20.63	24.37	28.96	34.77	35.87	48.2	59.5
	4	5.54	10.4	13.43	15.47	19.83	23.37	28.06	33.87	35.87	47.9	59.2
	5	5.54	10.4	13.43	15.47	19.83	23.37	28.16	33.97	35.87	47.9	59.2
	6	20.31	36.81	44.17	50.68	61.52	73.28	88.84	113.6	104.9	139	184.3
	7	19.23	35.34	44.13	50.68	61.52	71.98	87.64	110.9	103.3	136.8	182.1
	8	18.55	34.8	43.58	47.38	59.02	69.28	84.74	110.5	102.3	135.4	180.7
	9	18.11	33.81	42.62	46.38	58.42	69.18	85.14	109.6	102.3	135.4	180.7
	10	16.84	33.1	42.42	44.38	54.52	65.18	82.34	106.4	103.4	124.6	169.9
	11	5.42	10.5	12.13	17.47	18.23	21.67	25.96	31.77	31.67	42.5	54.3
	12	5.24	10.3	11.93	14.57	17.93	21.67	25.96	31.77	31.67	42.5	53.8
	13	5.24	10.3	11.93	14.37	18.03	21.87	25.66	31.47	31.87	42.9	53.2
	14	5.44	10.5	12.13	14.77	18.23	21.67	25.66	31.47	32.97	42.8	54.3
	15	6.44	11.4	13.73	15.77	18.93	23.37	27.66	33.97	33.87	43.2	55.6
Total		150	279.8	347.12	395.9	489.1	582.1	704.9	886.1	860.9	1129.7	1470

Table C65: Local Current of Individual Section for Increasing VApplied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 9.0 cm Flowrate = 7.9 Lit/ min

Temperature = 29 C Voidage = 0.85

CATHODE SECTION ↓	VOLTAGE (m V) → 50	100	150	200	250	300	350	400	450	500	550
1	6.71	9.24	10.76	12.9	14.86	16.43	16.86	20.4	29	35.3	38.15
2	5.95	8.29	10.56	11.8	14.06	16.33	16.86	20.2	27.8	35.1	37.95
3	5.95	7.69	10.06	11.3	13.86	14.83	15.76	19	26.7	33.1	35.95
4	5.71	8.09	10.06	11.3	13.06	13.83	14.86	18.1	26.7	32.8	35.65
5	5.71	8.09	10.06	11.3	13.06	13.83	14.96	18.2	26.7	32.8	35.65
6	15.39	21.98	25.12	28.4	28.84	29.52	30.44	44.9	62.6	73	84.5
7	14.31	20.71	25.08	28.4	28.84	28.22	29.24	42.2	61	70.8	82.3
8	13.63	19.97	24.53	25.1	26.34	25.52	26.34	41.8	60	69.4	80.9
9	11.29	17.08	21.67	22.2	23.84	23.52	24.84	39	58.1	67.5	79
10	10.02	16.37	21.47	20.2	19.94	19.52	22.04	35.8	59.2	56.7	68.2
11	4.39	6.99	7.56	12.1	10.26	10.93	11.56	14.8	21.3	26.1	29.55
12	4.21	6.79	7.36	9.2	9.96	10.93	11.56	14.8	21.3	26.1	29.05
13	4.21	6.79	7.36	9	10.06	11.13	11.26	14.5	21.5	26.5	28.45
14	4.39	6.99	7.55	9.4	10.26	10.93	11.26	14.5	22.6	26.7	29.55
15	5.5	7.89	9	10.6	10.96	12.73	13.36	17	23.7	26.8	30.85
Total	117.37	173	208.2	233.2	248.2	258.2	271.2	375.2	548.2	638.7	725.7

Table C66: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) | **Initial Bed Height = 9.0 cm** | Flowrate = 3.9 Lit/ min

Temperature = 29 C | Voidage = 0.61

← V O L T A G E (m V) →

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	6.24	9.28	11.13	13.7	15.79	17.13	17.26	22.4	31.8	37.7	40.62
2	5.48	8.33	10.93	12.6	14.99	17.03	17.26	22.2	30.6	37.5	40.42
3	5.48	7.73	10.43	12.1	14.79	15.53	16.16	21	29.5	35.5	38.42
4	5.24	8.13	10.43	12.1	13.99	14.53	15.26	20.1	29.5	35.2	38.12
5	5.24	8.13	10.43	12.1	13.99	14.53	15.36	20.2	29.5	35.2	38.12
6	18.91	27.53	31.97	37	37.96	37.72	37.44	58.3	79.2	88	99.8
7	17.83	26.06	31.93	37	37.96	36.42	36.24	55.6	77.6	85.8	97.6
8	17.15	25.52	31.38	33.7	35.46	33.72	33.34	55.2	76.6	84.4	96.2
9	16.71	24.53	30.42	32.7	34.86	33.62	33.74	54.3	76.6	84.4	96.2
10	17.4	15.44	30.22	30.7	30.96	29.62	30.94	51.1	77.7	73.6	85.4
11	5.32	7.59	8.16	12.7	10.86	14.53	15.16	18.4	24.9	29.7	30.7
12	4.81	7.39	7.96	9.8	10.56	11.53	12.16	15.4	21.9	26.7	29.65
13	4.81	7.39	7.96	9.6	10.66	11.73	11.86	15.1	22.1	27.1	29.05
14	4.99	7.59	8.15	10	10.86	11.53	11.86	15.1	23.2	27.3	30.15
15	6.1	8.49	9.6	11.2	11.56	13.33	13.96	17.6	24.3	27.4	31.45
Total	141.71	199.1	251.1	287	305.25	312.5	318	462	655	735.5	821.9

Table C67: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 9.0 cm Flowrate= 10.5 Lit/ min

Temperature = 29 C Voidage = 0.85

CATHODE SECTION	VOLTAGE (m V) 50	100	150	200	250	300	350	400	450	500	550
1	8.11	10.98	12.8	15.1	17.36	18.93	22.36	25.3	35.57	46.27	53.67
2	7.35	10.03	12.6	14	16.56	18.83	22.36	25.1	34.37	46.07	53.47
3	7.35	9.43	12.1	13.5	16.36	17.33	21.26	23.9	33.27	44.07	51.47
4	7.11	9.83	12.1	13.5	15.56	16.33	20.36	23	33.27	43.77	51.17
5	7.11	9.83	12.1	13.5	15.56	16.33	20.46	23.1	33.27	43.77	51.17
6	26.19	34.13	38.45	42.4	44.04	44.7	57.64	69.7	94.08	122.24	151.78
7	25.11	32.66	38.41	42.4	44.04	43.4	56.44	67	92.48	120.04	149.58
8	24.43	32.12	37.86	39.1	41.54	40.7	53.54	66.6	91.48	118.64	148.18
9	23.99	31.13	36.9	38.1	40.94	40.6	53.94	65.7	91.48	118.64	148.18
10	22.72	30.42	36.7	36.1	37.04	36.6	51.14	62.5	92.58	107.84	137.38
11	6.39	9.33	10.2	14.9	13.36	14.03	17.66	20.3	28.47	37.77	45.67
12	6.21	9.13	10	12	13.06	14.03	17.66	20.3	28.47	37.77	45.17
13	6.21	9.13	10	11.8	13.16	14.23	17.36	20	28.67	37.77	44.57
14	6.41	9.33	10.2	12	13.36	14.03	17.46	20	29.77	38.07	45.67
15	9.01	12.13	13.18	14.2	15.66	17.53	20.96	24.1	32.37	39.87	48.47
Total	193.7	259.6	303.6	332.6	357.6	367.6	470.6	556.6	779.6	1002.6	1225.6

Table C68: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 9.0 cm Flowrate =11.4 Lit/ min

Temperature = 29 C Voidage = 0.85

CATHODE SECTION	VOLTAGE (m V) → 50	100	150	200	250	300	350	400	450	500	550
1	8.82	12.38	14.5	17.14	19.22	20.17	21.04	25.7	35.97	46.67	54.07
2	7.86	11.43	14.3	16.04	18.22	20.07	21.04	25.5	34.77	46.47	53.87
3	7.86	10.83	13.8	15.54	18.02	18.57	19.94	24.3	33.67	44.47	51.87
4	7.62	11.23	13.8	15.54	17.22	17.57	19.04	23.4	33.67	44.17	51.57
5	7.62	11.23	13.8	15.54	17.22	17.57	19.14	23.5	33.67	44.17	51.57
6	26.23	37.73	43.25	48.56	48.68	47.7	50.33	69.3	93.7	121.68	151.38
7	25.15	36.26	43.21	48.56	48.68	46.4	49.13	66.6	92.1	119.48	149.18
8	24.47	35.72	42.64	45.26	46.18	43.7	46.23	66.2	91.1	118.08	147.78
9	24.03	34.73	41.7	44.26	44.36	43.6	46.63	65.3	91.1	118.08	147.78
10	22.76	34.02	41.5	42.26	41.68	39.6	43.83	62.1	92.2	107.28	136.98
11	6.7	10.53	11.7	16.74	14.82	15.07	16.14	20.5	28.67	37.97	45.87
12	6.52	10.33	11.5	13.84	14.52	15.07	16.14	20.5	28.67	37.97	45.37
13	6.52	10.33	11.5	13.64	13.64	15.27	15.84	20.2	28.87	38.37	44.77
14	6.74	10.83	11.7	14.04	14.05	15.07	15.84	20.2	29.97	38.47	45.87
15	7.64	11.43	13.1	15.04	15.49	16.77	21	22.7	30.87	38.67	47.07
Total	196.54	289	342	382	392	392.2	421.31	556	779	1002	1225

Table C69: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 9.0 cm Flowrate = 12.7 Lit/ min

Temperature = 29 C Voidage = 0.85

CATHODE SECTION ↓	VOLTAGE (mV) → 50	100	150	200	250	300	350	400	450	500	550
1	9.18	13.15	15.83	19.1	20.66	25.16	31.33	33.23	37.73	50	58.63
2	8.42	12.2	15.63	18	19.86	25.06	31.33	33.03	36.53	49.8	58.43
3	8.42	11.6	15.13	17.5	19.66	23.56	30.23	31.83	35.43	47.8	56.43
4	8.18	12	15.13	17.5	18.86	22.56	29.33	30.93	35.43	47.5	56.13
5	8.18	12	15.13	17.5	18.86	22.56	29.43	31.03	35.43	47.5	56.13
6	29.07	41.41	49.17	57	55.84	68.24	92.12	100	101.3	135.6	170.22
7	27.99	39.94	49.13	57	55.84	66.94	90.92	97.32	99.72	133.4	168.02
8	27.31	39.4	48.58	53.7	53.34	64.24	88.02	96.92	98.72	132	166.62
9	26.87	38.41	47.62	52.7	52.74	64.14	88.42	96.02	98.72	132	166.62
10	25.6	37.7	47.42	50.7	48.84	60.14	85.62	92.82	99.82	121.2	155.82
11	7.56	11.6	13.33	19	16.76	20.36	26.73	28.33	30.73	41.6	50.73
12	7.38	11.4	13.13	16.1	16.46	20.36	26.73	28.33	30.73	41.6	50.23
13	7.38	11.4	13.13	15.9	16.56	20.56	26.43	28.03	30.93	42	49.63
14	7.58	11.6	13.33	16.3	16.76	20.36	26.43	28.03	32.03	41.9	50.73
15	8.58	12.5	14.93	17.3	17.46	22.06	28.43	30.53	32.93	42.3	52.03
Total	217.7	316.3	386.62	445.3	448.5	546.3	731.5	786.4	836.2	1106.2	1366.4

Table C70: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 9.0 cm Flowrate = 14.7 Lit/ min

Temperature = 29 C Voidage = 0.85

← V O L T A G E →
(m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	9.44	14.72	18.8	20.93	25.46	30	35.86	41.57	50.77	63.7	78
2	8.68	13.77	18.6	19.83	24.66	29.9	35.86	41.37	49.57	63.5	77.8
3	8.68	13.17	18.1	19.33	24.46	28.4	34.76	40.17	48.47	61.5	75.8
4	8.44	13.57	18.1	19.33	23.66	27.4	33.86	39.27	48.47	61.2	75.5
5	8.44	13.57	18.1	19.33	23.66	27.4	33.96	39.37	48.47	61.2	75.5
6	28.81	46.39	59.75	63.02	73.74	86.3	108.94	132.1	152.2	189.1	246.4
7	27.73	44.92	59.71	63.02	73.74	85	107.74	129.4	150.6	186.9	244.2
8	27.05	44.38	59.16	59.72	71.24	82.3	104.84	129	149.6	185.5	242.8
9	26.61	43.39	58.2	58.72	70.64	82.2	105.24	128.1	149.6	185.5	242.8
10	25.34	42.63	58	56.72	66.74	78.2	102.44	124.9	150.7	174.7	232
11	7.92	13.27	16.4	20.93	21.66	25.3	31.36	36.77	43.87	55.4	70.2
12	7.74	13.07	16.2	18.03	21.36	25.3	31.36	36.77	43.87	55.4	69.7
13	7.74	13.07	16.2	17.83	21.46	25.5	31.06	36.47	44.07	55.8	69.1
14	7.94	13.27	16.4	18.23	21.66	25.3	31.06	36.47	45.17	55.7	70.2
15	8.94	14.17	18	19.23	22.36	27	33.06	38.97	46.07	56.1	71.5
Total	219.5	357.4	469.72	494.2	586.5	685.5	861.4	1031	1222	1511.2	1941.5

Table C71: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 12.0 cm Flowrate = 5.8 Lit/ min

Temperature = 29 C Voidage = 0.8

← V O L T A G E →
(m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	9.14	14.15	16.73	19.67	24.23	28.57	32.66	38.77	40.77	53	64.3
2	9.14	13.2	16.53	18.57	23.43	28.47	32.66	38.57	38.57	52.8	64.1
3	8.38	12.6	16.03	18.07	23.23	26.97	31.56	37.37	38.47	50.8	62.1
4	8.14	13	16.03	18.07	22.43	25.97	30.66	36.47	38.47	50.5	61.8
5	8.14	13	16.03	18.07	22.43	25.97	30.76	36.57	38.47	50.5	61.8
6	27.41	43.91	51.27	57.78	68.62	80.38	95.94	120.7	112	146.1	191.4
7	26.33	42.44	51.23	57.78	68.62	79.08	94.74	118	110.4	143.9	189.2
8	25.65	41.9	50.68	54.48	66.12	76.38	91.84	117.6	109.4	142.5	187.8
9	25.21	40.91	49.72	53.48	65.52	76.28	92.24	116.7	109.4	142.5	187.8
10	22.04	38.3	47.62	49.58	59.72	70.38	87.54	111.6	108.6	129.8	175.1
11	7.52	12.6	14.23	19.57	20.33	23.77	28.06	33.87	33.77	44.6	56.4
12	7.34	12.4	14.03	16.67	20.03	23.77	28.06	33.87	33.77	44.6	55.9
13	7.34	12.4	14.03	16.47	20.13	23.97	27.76	33.57	33.97	45	55.3
14	7.54	12.6	14.23	16.87	20.33	23.77	27.76	33.57	35.07	44.9	56.4
15	8.54	13.5	15.83	17.87	21.03	25.47	29.76	36.07	35.97	45.3	57.7
Total	207.86	336.9	404.22	453	546.2	639.2	762	943.2	918	1186.8	1527.1

Table C72: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 12.0 cm Flowrate = 7.9 Lit/ min

Temperature = 29 C Voidage = 0.8

← V O L T A G E (m V) →

CATHODE SECTION ↓											
1	9.41	11.94	13.46	15.6	17.56	19.13	19.56	23.1	31.7	38	40.85
2	8.65	10.99	13.26	14.5	16.76	19.03	19.56	22.9	30.5	37.8	40.65
3	8.65	10.39	12.76	14	16.56	17.53	18.46	21.7	29.4	35.8	38.65
4	8.41	10.79	12.76	14	15.76	16.53	17.56	20.8	29.4	35.5	38.35
5	8.41	10.79	12.76	14	15.76	16.53	17.66	20.9	29.4	35.5	38.35
6	22.79	29.38	32.52	35.8	36.24	36.92	37.84	52.3	70	75.7	87.2
7	21.71	28.11	32.48	35.8	36.24	35.62	36.64	49.6	68.4	73.5	85
8	21.03	27.37	31.93	32.5	33.74	32.92	33.74	49.2	67.4	72.1	83.6
9	18.69	24.48	29.07	29.6	31.24	30.92	32.24	46.4	65.5	70.2	81.7
10	15.32	21.67	26.77	25.5	25.24	24.82	27.34	41.1	64.5	59.4	70.9
11	7.09	9.69	10.26	14.8	12.96	13.63	14.26	17.5	24	28.8	32.25
12	6.91	9.49	10.06	11.9	12.66	13.63	14.26	17.5	24	28.8	31.75
13	6.91	9.49	10.06	11.7	12.76	13.83	13.96	17.2	24.2	29.2	31.15
14	7.09	9.69	10.25	12.1	12.96	13.63	13.96	17.2	25.3	29.4	32.25
15	8.2	10.59	11.7	13.3	13.66	15.43	16.06	19.7	26.4	29.5	33.55
Total	179.27	234.9	270.1	295.1	310.1	320.1	333.1	437.1	610.1	679.2	766.2

Table C73: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 12.0 cm Flowrate =8.9 Lit/ min

Temperature = 29 C Voidage = 0.85

CATHODE SECTION ↓	VOLTAGE (m V) → 50	100	150	200	250	300	350	400	450	500	550
1	8.64	11.68	13.53	16.1	18.19	19.53	19.66	24.8	34.2	40.1	43.02
2	7.88	10.73	13.33	15	17.39	19.43	19.66	24.6	33	39.9	42.82
3	7.88	10.13	12.83	14.5	17.19	17.93	18.56	23.4	31.9	37.9	40.82
4	7.64	10.53	12.83	14.5	16.39	16.93	17.66	22.5	31.9	37.6	40.52
5	7.64	10.53	12.83	14.5	16.39	16.93	17.76	22.6	31.9	37.6	40.52
6	26.31	34.93	39.37	44.4	45.36	45.12	44.84	65.7	86.9	95.4	107.2
7	25.23	33.46	39.33	44.4	45.36	43.82	43.64	63	85	93.2	105
8	24.55	32.92	38.78	41.1	42.86	41.12	40.74	62.6	84	91.8	103.6
9	24.11	31.93	37.82	40.1	42.26	41.02	41.14	61.7	84	91.8	103.6
10	24.8	22.84	37.62	38.1	38.36	37.02	38.34	58.5	85.1	81	92.8
11	7.62	9.89	10.46	15	13.16	16.83	17.46	20.7	27.2	32	33
12	6.81	9.39	9.96	11.8	12.56	13.53	14.16	17.4	23.9	28.7	31.65
13	6.81	9.39	9.96	11.6	12.65	13.73	13.86	17.1	24.1	29.1	31.05
14	6.99	9.59	10.15	12	12.86	13.53	13.86	17.1	25.2	29.3	32.15
15	9.1	11.49	12.6	14.2	14.56	16.33	16.96	20.6	27.3	30.4	34.45
Total	202.01	259.4	311.4	347.3	365.55	372.8	378.3	522.3	715.3	795.8	882.2

Table C74: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 12.0 cm Flowrate = 10.5Lit/ min

Temperature = 29 C Voidage = 0.85

← V O L T A G E →
(m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	10.51	13.38	15.2	17.5	19.76	21.33	24.76	27.7	37.97	48.67	56.07
2	9.75	12.43	15	16.4	18.96	21.23	24.76	27.5	36.77	48.47	55.87
3	9.75	11.83	14.5	15.9	18.76	19.73	23.66	26.3	35.67	46.47	53.87
4	9.51	12.23	14.5	15.9	17.96	18.73	22.76	25.4	35.67	46.17	53.57
5	9.51	12.23	14.5	15.9	17.96	18.73	22.86	25.5	35.67	46.17	53.57
6	32.39	40.33	44.65	48.6	50.24	50.9	63.84	75.9	100.3	128.44	157.98
7	31.31	38.86	44.61	48.6	50.24	49.6	62.64	73.2	98.68	126.24	155.78
8	30.63	38.32	44.06	45.3	47.74	46.9	59.74	72.8	97.68	124.84	154.38
9	30.19	37.33	43.1	44.3	47.14	46.8	60.14	71.9	97.68	124.84	154.38
10	28.92	36.62	42.9	42.3	43.24	42.8	57.34	68.7	98.78	114.04	143.58
11	8.59	11.53	12.4	17.1	15.56	16.23	19.86	22.5	30.67	39.97	47.87
12	8.41	11.33	12.2	14.2	15.26	16.23	19.86	22.5	30.67	39.97	47.37
13	8.41	11.33	12.2	14	15.36	16.43	19.56	22.2	30.87	39.97	46.77
14	7.91	10.83	11.7	13.5	14.86	15.53	18.96	21.5	31.27	39.57	47.17
15	11.51	14.63	15.68	16.7	18.16	20.03	23.46	26.6	34.87	42.37	50.97
Total	247.3	313.2	357.2	386.2	411.2	421.2	524.2	610.2	833.2	1056.2	1279.2

Table C75: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) | Initial Bed Height = 12.0 cm | Flowrate =11.4 Lit/ min

Temperature = 29 C | Voidage = 0.8

← V O L T A G E →
(m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	11.32	14.88	17	19.64	21.72	22.67	23.54	28.2	38.47	49.17	56.57
2	10.36	13.93	16.8	18.54	20.72	22.57	23.54	28	37.27	48.97	56.37
3	10.36	13.33	16.3	18.04	20.52	21.07	22.44	26.8	36.17	46.97	54.37
4	10.12	13.73	16.3	18.04	19.72	20.07	21.54	25.9	36.17	46.67	54.07
5	10.12	13.73	16.3	18.04	19.72	20.07	21.64	26	36.17	46.67	54.07
6	33.03	44.53	50.05	55.36	55.48	54.5	57.13	76.1	100.5	128.48	158.18
7	31.95	43.06	50.01	55.36	55.48	53.2	55.93	73.4	98.9	126.28	155.98
8	31.27	42.52	49.44	52.06	52.98	50.5	53.03	73	97.9	124.88	154.58
9	30.83	41.53	48.5	51.06	51.16	50.4	53.43	72.1	97.9	124.88	154.58
10	29.56	40.82	48.3	49.06	48.48	46.4	50.63	68.9	99	114.08	143.78
11	8.9	12.73	13.9	18.94	17.02	17.27	18.34	22.7	30.87	40.17	48.07
12	8.72	12.53	13.7	16.04	16.72	17.27	18.34	22.7	30.87	40.17	47.57
13	8.72	12.53	13.7	15.84	15.84	17.47	18.04	22.4	31.07	40.57	46.97
14	8.24	12.33	13.2	15.54	15.55	16.57	17.34	21.7	31.47	39.97	47.37
15	10.84	14.63	16.3	18.24	18.69	19.97	24.2	25.9	34.07	41.87	50.27
Total	254.34	346.8	399.8	439.8	449.8	450	479.11	613.8	836.8	1059.8	1282.8

Table C76: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 12.0 cm Flowrate = 12.7 Lit/ min

Temperature = 29 C Voidage = 0.8

← V O L T A G E →
(m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	11.68	15.65	18.33	21.6	23.16	27.66	33.83	35.73	40.23	52.5	61.13
2	10.92	14.7	18.13	20.5	22.36	27.56	33.83	35.53	39.03	52.3	60.93
3	10.92	14.1	17.63	20	22.16	26.06	32.73	34.33	37.93	50.3	58.93
4	10.68	14.5	17.63	20	21.36	25.06	31.83	33.43	37.93	50	58.63
5	10.68	14.5	17.63	20	21.36	25.06	31.93	33.53	37.93	50	58.63
6	36.17	48.51	56.27	64.1	62.94	75.34	99.22	107.1	108.4	142.7	177.32
7	35.09	47.04	56.23	64.1	62.94	74.04	98.02	104.4	106.8	140.5	175.12
8	34.41	46.5	55.68	60.8	60.44	71.34	95.12	104	105.8	139.1	173.72
9	33.97	45.51	54.72	59.8	59.84	71.24	95.52	103.1	105.8	139.1	173.72
10	32.7	44.8	54.52	57.8	55.94	67.24	92.72	99.92	106.9	128.3	162.92
11	10.06	14.1	15.83	21.5	19.26	22.86	29.23	30.83	33.23	44.1	53.23
12	9.88	13.9	15.63	18.6	18.96	22.86	29.23	30.83	33.23	44.1	52.73
13	9.88	13.9	15.63	18.4	19.06	23.06	28.93	30.53	33.43	44.5	52.13
14	10.08	14.1	15.83	18.8	19.26	22.86	28.93	30.53	34.53	44.4	53.23
15	11.08	15	17.43	19.8	19.96	24.56	30.93	33.03	35.43	44.8	54.53
Total	278.2	376.8	447.12	505.3	509	606.8	792	846.9	896.7	1166.7	1426.9

Table C77: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 12.0 cm Flowrate = 14.6Lit/ min

Temperature = 29 C Voidage = 0.8

← V O L T A G E → (m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	11.64	16.92	21	23.13	27.66	32.2	38.06	43.77	52.97	65.9	80.2
2	10.88	15.97	20.8	22.03	26.86	32.1	38.06	43.57	51.77	65.7	80
3	10.88	15.37	20.3	21.53	26.66	30.6	36.96	42.37	50.67	63.7	78
4	10.64	15.77	20.3	21.53	25.86	29.6	36.06	41.47	50.67	63.4	77.7
5	10.64	15.77	20.3	21.53	25.86	29.6	36.16	41.57	50.67	63.4	77.7
6	35.11	52.69	66.05	69.32	80.04	92.6	115.24	138.4	158.5	195.4	252.7
7	34.03	51.22	66.01	69.32	80.04	91.3	114.04	135.7	156.9	193.2	250.5
8	33.35	50.68	65.46	66.02	77.54	88.6	111.14	135.3	155.9	191.8	249.1
9	32.91	49.69	64.5	65.02	76.94	88.5	111.54	134.4	155.9	191.8	249.1
10	31.64	48.98	64.3	63.02	73.04	84.5	108.74	131.2	157	181	238.3
11	10.12	15.47	18.6	23.13	23.86	27.5	33.56	38.97	46.07	57.6	72.4
12	9.94	15.27	18.4	20.23	23.56	27.5	33.56	38.97	46.07	57.6	71.9
13	9.94	15.27	18.4	20.03	23.66	27.7	33.26	38.67	46.27	58	71.3
14	10.14	15.47	18.6	20.43	23.86	27.5	33.26	38.67	47.37	57.9	72.4
15	11.14	16.37	20.2	21.43	24.56	29.2	35.26	41.17	48.27	58.3	73.7
Total	273	410.9	523.22	547.7	640	739	914.9	1084	1275	1564.7	1995

Table C78: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 15.0 cm Flowrate = 5.8 Lit/ min

Temperature = 29 C Voidage = 0.75

VOLTAGE (m V) →

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	6.44	11.45	14.03	16.97	21.53	25.87	29.96	36.07	38.07	50.3	61.6
2	6.44	10.5	13.83	15.87	20.73	25.77	29.96	35.87	36.87	50.1	61.4
3	5.68	9.9	13.33	15.37	20.53	24.27	28.86	34.67	35.77	48.1	59.4
4	5.44	10.3	13.33	15.37	19.73	23.27	27.96	33.77	35.77	47.8	59.1
5	5.44	10.3	13.33	15.37	19.73	23.27	28.06	33.87	35.77	47.8	59.1
6	22.71	39.21	46.57	53.08	63.92	75.68	91.24	116	107.3	141.4	186.7
7	21.63	37.74	46.53	53.08	63.92	74.38	90.04	113.3	105.7	139.2	184.5
8	20.95	37.2	45.98	49.78	61.42	71.68	87.14	112.9	104.7	137.8	183.1
9	20.51	36.21	45.02	48.78	60.82	71.58	87.54	112	104.7	137.8	183.1
10	17.34	33.6	42.92	44.88	55.02	65.68	82.84	106.9	103.9	125.1	170.4
11	5.82	10.9	12.53	17.87	18.53	22.07	26.36	32.17	32.07	42.9	54.7
12	5.64	10.7	12.33	14.97	18.33	22.07	26.36	32.17	32.07	42.9	54.2
13	5.64	10.7	12.33	14.77	18.43	22.27	26.06	31.87	32.27	43.3	53.6
14	5.84	10.9	12.53	15.17	18.63	22.07	26.06	31.87	33.37	43.2	54.7
15	6.84	11.8	14.13	16.17	19.33	23.77	28.06	34.37	34.27	43.6	56
Total	162.36	291.4	358.72	407.5	500.7	593.7	716.5	897.7	872.5	1141.3	1481.6

Table C79: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 15.0 cm Flowrate =7.9 Lit/ min

Temperature = 29 C Voidage = 0.75

← V O L T A G E → (m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	6.71	9.24	10.76	12.9	14.86	16.43	16.86	20.4	29	35.3	33.15
2	5.95	8.29	10.56	11.8	14.06	16.33	16.86	20.2	27.8	35.1	37.95
3	5.95	7.69	10.06	11.3	13.86	14.83	15.76	19	26.7	33.1	35.95
4	5.71	8.09	10.06	11.3	13.06	13.83	14.86	18.1	26.7	32.8	35.65
5	5.71	8.09	10.06	11.3	13.06	13.83	14.96	18.2	26.7	32.8	35.65
6	17.09	23.68	26.82	30.1	30.54	31.22	32.14	46.6	64.3	70	81.5
7	16.01	22.41	26.78	30.1	30.54	29.92	30.94	43.9	62.7	67.8	79.3
8	15.33	21.67	26.23	26.8	28.04	27.22	28.04	43.5	61.7	66.4	77.9
9	12.99	18.78	23.37	23.9	25.54	25.22	26.54	40.7	59.8	64.5	76
10	9.62	15.97	21.07	19.8	19.54	19.12	21.64	35.4	58.8	53.7	65.2
11	5.29	7.89	8.46	13	11.16	11.83	12.46	15.7	22.2	27	30.45
12	5.11	7.69	8.26	10.1	10.86	11.83	12.46	15.7	22.2	27	29.95
13	5.11	7.69	8.26	9.9	10.96	12.03	12.16	15.4	22.4	27.4	29.35
14	5.29	7.89	8.45	10.3	11.16	11.83	12.16	15.4	23.5	27.6	30.45
15	6.4	8.79	9.9	11.5	11.86	13.63	14.26	17.9	24.6	27.7	31.75
Total	128.27	183.9	219.1	244.1	259.1	269.1	282.1	386.1	559.1	628.2	715.2

Table C80: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 15.0 cm Flowrate = 8.7 Lit/ min

Temperature = 29 C Voidage = 0.75

← V O L T A G E →
(m A)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	6.34	9.38	11.23	13.8	15.89	17.23	17.36	22.5	31.9	37.8	40.72
2	5.58	8.43	11.03	12.7	15.09	17.13	17.36	22.3	30.7	37.6	40.52
3	5.58	7.83	10.53	12.2	14.89	15.63	16.26	21.1	29.6	35.6	38.52
4	5.34	8.23	10.53	12.2	14.09	14.63	15.36	20.2	29.6	35.3	38.22
5	5.34	8.23	10.53	12.2	14.09	14.63	15.46	20.3	29.6	35.3	38.22
6	20.91	29.53	33.97	39	39.96	39.72	39.44	60.3	81.2	90	101.8
7	19.83	28.06	33.93	39	39.96	38.42	38.24	57.6	79.6	87.8	99.6
8	19.15	27.52	33.38	35.7	37.46	35.72	35.34	57.2	78.6	86.4	98.2
9	18.71	26.53	32.42	34.7	36.86	35.62	35.74	56.3	78.6	86.4	98.2
10	19.4	17.44	32.22	32.7	32.96	31.62	32.94	53.1	79.7	75.6	87.4
11	6.22	8.49	9.06	13.6	11.76	15.43	16.06	19.3	25.8	30.6	31.6
12	5.41	7.99	8.56	10.4	11.16	12.13	12.76	16	22.5	27.3	30.25
13	5.41	7.99	8.56	10.2	11.26	12.33	12.46	15.7	22.7	27.7	29.65
14	5.59	8.19	8.75	10.6	11.46	12.13	12.46	15.7	23.8	27.9	30.75
15	7.7	10.09	11.2	12.8	13.16	14.93	15.56	19.2	25.9	29	33.05
Total	156.51	213.9	265.9	301.8	320.05	327.3	332.8	476.8	669.8	750.3	836.7

Table C81: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 15.0 cm Flowrate = 10.5 Lit/ min

Temperature = 29 C Voidage = 0.75

← V O L T A G E →
(m A)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	8.01	10.88	12.7	15	17.26	18.83	22.26	25.2	35.47	46.17	53.57
2	7.25	9.93	12.5	13.9	16.46	18.73	22.26	25	34.27	45.97	53.37
3	7.25	9.33	12	13.4	16.26	17.23	21.16	23.8	33.17	43.97	51.37
4	7.01	9.73	12	13.4	15.46	16.23	20.26	22.9	33.17	43.67	51.07
5	7.01	9.73	12	13.4	15.46	16.23	20.36	23	33.17	43.67	51.07
6	27.89	35.83	40.15	44.1	45.74	46.4	59.34	71.4	95.78	123.94	153.48
7	26.81	34.36	40.11	44.1	45.74	45.1	58.14	66.7	94.18	121.74	151.28
8	26.13	33.82	39.56	40.8	43.24	42.4	55.24	68.3	93.18	120.34	149.88
9	25.69	32.83	38.6	39.8	42.64	42.3	55.64	67.4	93.18	120.34	149.88
10	24.42	32.12	38.4	37.8	38.74	38.3	52.84	64.2	94.28	109.54	139.08
11	6.09	9.03	9.9	14.6	13.06	13.73	17.36	20	28.17	37.47	45.37
12	5.91	8.83	9.7	11.7	12.76	13.73	17.36	20	28.17	37.47	44.87
13	5.91	8.83	9.7	11.5	12.86	13.93	17.06	19.7	28.37	37.47	44.27
14	5.41	8.33	9.2	11	12.36	13.03	16.46	19	28.77	37.07	44.67
15	9.01	12.13	13.18	14.2	15.66	17.53	20.96	24.1	32.37	39.87	48.47
Total	199.8	265.7	309.7	338.7	363.7	373.7	476.7	562.7	785.7	1008.7	1231.7

Table C82: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) **Initial Bed Height = 15.0 cm** Flowrate = 11.4 Lit/ min

Temperature = 29 C Voidage = 0.75

← V O L T A G E (m V) →

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	8.72	12.28	14.4	17.04	19.12	20.07	20.94	25.6	35.87	46.57	53.97
2	7.76	11.33	14.2	15.94	18.12	19.97	20.94	25.4	34.67	46.37	53.77
3	7.76	10.73	13.7	15.44	17.92	18.47	19.84	24.2	33.57	44.37	51.77
4	7.52	11:13	13.7	15.44	17.12	17.47	18.94	23.3	33.57	44.07	51.47
5	7.52	11:13	13.7	15.44	17.12	17.47	19.04	23.4	33.57	44.07	51.47
6	30.43	41.93	47.45	52.76	52.88	51.9	54.53	73.5	97.9	125.88	155.58
7	29.35	40.46	47.41	52.76	52.88	50.6	53.33	70.8	96.3	123.68	153.38
8	28.67	39.92	46.84	49.46	50.38	47.9	50.43	70.4	95.3	122.28	151.98
9	28.23	38.93	45.9	48.46	48.56	47.8	50.83	69.5	95.3	122.28	151.98
10	26.96	38.22	45.7	46.46	45.88	43.8	48.03	66.3	96.4	111.48	141.18
11	6.3	10.13	11.3	16.34	14.42	14.67	15.74	20.1	28.27	37.57	45.47
12	6.12	9.93	11.1	13.44	14.12	14.67	15.74	20.1	28.27	37.57	44.97
13	6.12	9.93	11.1	13.24	13.24	14.87	15.44	19.8	28.47	37.97	44.37
14	5.64	9.73	10.6	12.94	12.95	13.97	14.74	19.1	28.87	37.37	44.77
15	8.24	12.03	13.7	15.64	16.09	17.37	21.6	23.3	31.47	39.27	47.67
Total	215.34	307.8	360.8	400.8	410.8	411	440.11	574.8	797.8	1020.8	1243.8

Table C83: Local Current of Individual Section for Increasing Applied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 15.0 cm Flowrate = 12.7 Lit/ min

Temperature = 29 C Voidage = 0.75

← V O L T A G E →
(m V)

CATHODE SECTION ↓	50	100	150	200	250	300	350	400	450	500	550
1	9.08	13.05	15.73	19	20.56	25.06	31.23	33.13	37.63	49.9	58.53
2	8.32	12.1	15.53	17.9	19.76	24.96	31.23	32.93	36.43	49.7	58.33
3	8.32	11.5	15.03	17.4	19.56	23.46	30.13	31.73	35.33	47.7	56.33
4	8.08	11.9	15.03	17.4	18.76	22.46	29.23	30.83	35.33	47.4	56.03
5	8.08	11.9	15.03	17.4	18.76	22.46	29.33	30.93	35.33	47.4	56.03
6	29.57	41.91	49.67	57.5	56.34	68.74	92.62	100.5	101.8	136.1	170.72
7	28.49	40.44	49.63	57.5	56.34	67.44	91.42	97.82	100.2	133.9	168.52
8	27.81	39.9	49.08	54.2	53.84	64.74	88.52	97.42	99.22	132.5	167.12
9	27.37	38.91	48.12	53.2	53.24	64.64	88.92	96.52	99.22	132.5	167.12
10	26.1	38.2	47.92	51.2	49.34	60.64	86.12	93.32	100.3	121.7	156.32
11	7.46	11.5	13.23	18.9	16.66	20.26	26.63	28.23	30.63	41.5	50.63
12	7.28	11.3	13.03	16	16.36	20.26	26.63	28.23	30.63	41.5	50.13
13	7.28	11.3	13.03	15.8	16.46	20.46	26.33	27.93	30.83	41.9	49.53
14	7.48	11.5	13.23	16.2	16.66	20.26	26.33	27.93	31.93	41.8	50.63
15	8.48	12.4	14.83	17.2	17.36	21.96	28.33	30.43	32.83	42.2	51.93
Total	219.2	317.8	388.12	446.8	450	547.8	733	787.9	837.7	1107.7	1367.9

Table C84: Local Current of Individual Section for increasing Applied Voltage

Particle Size = 3mm (dia) Initial Bed Height = 15.0 cm Flowrate = 14.6Lit/min

Temperature = 29 C Voidage = 0.75

VOLTAGE (m V)

CATHODE SECTION	50	100	150	200	250	300	350	400	450	500	550
1	6.78	10.75	13.43	16.7	18.26	22.76	28.93	30.83	35.33	47.6	56.23
2	6.02	9.8	13.23	15.6	17.46	22.66	28.93	30.63	34.13	47.4	56.03
3	6.02	9.2	12.73	15.1	17.26	21.16	27.83	29.43	33.03	45.4	54.03
4	5.78	9.6	12.73	15.1	16.46	20.16	26.93	28.53	33.03	45.1	53.73
5	5.78	9.6	12.73	15.1	16.46	20.16	27.03	28.63	33.03	45.1	53.73
6	24.27	36.61	44.37	52.2	51.04	63.44	87.32	95.22	96.52	130.8	165.42
7	23.19	35.14	44.33	52.2	51.04	62.14	86.12	92.52	94.92	128.6	163.22
8	22.51	34.6	43.78	48.9	48.54	59.44	83.22	92.12	93.92	127.2	161.82
9	22.07	33.61	42.82	47.9	47.94	59.34	83.62	91.22	93.92	127.2	161.82
10	20.8	32.9	42.62	45.9	44.04	55.34	80.82	88.02	95.02	116.4	151.02
11	5.16	9.2	10.93	16.6	14.36	17.96	24.33	25.93	28.33	39.2	48.33
12	4.98	9	10.73	13.7	14.06	17.96	24.33	25.93	28.33	39.2	47.83
13	4.98	9	10.73	13.5	14.16	18.16	24.03	25.63	28.53	39.6	47.23
14	5.18	9.2	10.93	13.9	14.36	17.96	24.03	25.63	29.63	39.5	48.33
15	6.18	10.1	12.53	14.9	15.06	15.66	26.03	28.13	30.53	39.9	49.63
Total	169.7	268.3	338.62	397.3	400.5	498.3	683.5	738.4	788.2	1058.2	1318.4

APPENDIX - D

CALCULATED DATA

Table D1 : Overall Limiting Current and Mass Transfer Coefficient For Particle Size = 1 mm at Different Initial Bed Height

	Initial Bed Height (cm)							
	6		9		12		15	
Flow Rate Liter/min	i_L m.amp	Kav × 10^6 m/s	i_L m.amp	Kav × 10^6 m/s	i_L m.amp	Kav × 10^6 m/s	i_L m.amp	Kav × 10^6 m/s
5.8	227.55	1.31	243.18	1.4	303.98	1.75	272.71	1.57
7.9	243.18	1.4	269.24	1.55	371.72	2.14	319.61	1.84
8.9	264.02	1.52	300.5	1.73	397.77	2.29	349.14	2.01
10.5	305.71	1.76	343.93	1.98	460.31	2.65	409.93	2.36
11.4	330.03	1.9	383.88	2.21	491.57	2.83	441.2	2.54
12.7	382.14	2.2	444.67	2.56	517.63	2.98	477.68	2.75
14.6	442.94	2.55	474.2	2.73	555.84	3.2	514.15	2.96
16.3	416.88	2.4	449.88	2.59	531.52	3.06	595.05	2.85

Table D2 : Overall Limiting Current and Mass Transfer Coefficient For Particle Size = 2 mm at Different Initial Bed Height

	Initial Bed Height (cm)							
	6		9		12		15	
Flow Rate Liter/min	i_L m.amp	Kav × 10^6 m/s	i_L m.amp	Kav × 10^6 m/s	i_L m.amp	Kav × 10^6 m/s	i_L m.amp	Kav × 10^6 m/s
5.8	350.87	2.02	368.24	2.12	429.04	2.47	390.83	2.25
7.9	399.51	2.3	430.78	2.48	496.78	2.86	458.57	2.64
8.9	422.09	2.43	463.78	2.67	547.16	3.15	505.47	2.91
10.5	458.57	2.64	526.31	3.03	604.48	3.48	571.47	3.29
11.4	481.15	2.77	547.16	3.15	642.69	3.7	602.74	3.47
12.7	514.15	2.96	576.68	3.32	675.69	3.89	637.48	3.67
14.6	533.26	3.07	588.84	3.39	706.96	4.07	665.27	3.83
16.3	512.42	2.95	562.79	3.24	689.59	3.97	647.9	3.73

Table D3 : Overall Limiting Current and Mass Transfer Coefficient For Particle Size = 3 mm at Different Initial Bed Height

	Initial Bed Height (cm)							
	6		9		12		15	
Flow Rate Liter/min	i_L m.amp	Kav × 10^6 m/s	i_L m.amp	Kav × 10^6 m/s	i_L m.amp	Kav × 10^6 m/s	i_L m.amp	Kav × 10^6 m/s
5.8	420.35	2.42	437.72	2.52	498.52	2.87	460.31	2.65
7.9	468.99	2.7	500.26	2.88	566.26	3.26	528.05	3.04
8.9	491.57	2.83	533.26	3.07	616.64	3.55	574.95	3.31
10.5	528.05	3.04	595.79	3.43	673.96	3.88	640.95	3.69
11.4	550.63	3.17	616.64	3.55	712.17	4.10	672.22	3.87
12.7	583.63	3.36	646.16	3.72	745.17	4.29	706.96	4.07
14.6	620.11	3.57	675.69	3.89	793.81	4.57	752.12	4.33
16.3	634.01	3.65	684.38	3.94	811.18	4.67	769.49	4.43

Table D4 : Sherwood Number and Reynolds Number For Particle Size = 1 mm at Different Initial Bed Height

	Initial Bed Height (cm)							
	6		9		12		15	
Flow Rate Liter/min	Re	Sh*10^2	Re	Sh*10^2	Re	Sh*10^2	Re	Sh*10^2
5.8	273.34	60.38	182.23	64.53	136.67	80.66	109.34	72.36
7.9	371.20	64.53	247.47	71.44	185.60	98.63	148.48	84.81
8.9	416.76	70.06	277.84	79.74	208.38	105.54	166.7	92.64
10.5	492.69	81.19	328.46	91.26	246.34	122.14	197.08	108.77
11.4	533.18	87.57	355.46	101.86	266.59	130.43	213.27	117.07
12.7	597.30	101.40	398.20	117.99	298.65	137.35	238.92	126.75
14.6	685.04	117.53	456.69	125.82	342.52	147.49	274.02	136.42
16.3	762.65	110.61	508.44	119.37	381.33	141.03	305.06	131.36

Table D5 : Sherwood Number and Reynolds Number For Particle Size = 2 mm at Different Initial Bed Height

	Initial Bed Height (cm)							
	6		9		12		15	
Flow Rate Liter/min	Re	Sh*10^2	Re	Sh*10^2	Re	Sh*10^2	Re	Sh*10^2
5.8	546.68	93.1	364.45	97.71	273.34	113.84	218.67	103.70
7.9	742.41	106.01	494.94	114.30	371.20	131.82	296.96	121.68
8.9	833.52	112.00	555.68	123.06	416.76	145.18	333.41	134.12
10.5	985.38	121.68	656.92	139.65	492.69	160.39	394.15	151.63
11.4	1066.4	127.67	710.91	145.18	533.18	170.53	426.55	159.93
12.7	1194.6	136.42	796.40	153.02	597.30	179.29	477.84	169.15
14.6	1370.1	141.49	913.39	156.24	685.04	187.58	548.03	176.52
16.3	1525.3	135.96	1016.9	149.33	762.65	182.98	610.12	171.91

Table D6 : Sherwood Number and Reynolds Number For Particle Size = 3 mm at Different Initial Bed Height

	Initial Bed Height (cm)							
	6		9		12		15	
Flow Rate Liter/min	Re	Sh*10^2	Re	Sh*10^2	Re	Sh*10^2	Re	Sh*10^2
5.8	820.02	111.54	546.68	116.15	410.01	132.28	328.01	122.14
7.9	1113.6	124.44	742.41	132.74	556.81	150.25	445.44	140.11
8.9	1250.3	130.43	833.52	141.49	625.14	163.62	500.11	152.56
10.5	1478.1	140.11	985.38	158.09	739.03	178.83	591.23	170.07
11.4	1599.6	146.10	1066.4	163.62	799.78	188.97	639.82	178.37
12.7	1791.9	154.86	1194.6	171.45	895.95	197.72	716.76	187.58
14.6	2055.1	164.54	1370.1	179.29	1027.6	210.63	822.05	199.57
16.3	2288.0	168.23	1525.3	181.59	1144.0	215.24	915.19	204.18