Design of electromagnetic system to predict interface movement and homogeneous state of solid - liquid system by dimensional analysis under the influence of induced electric field

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Abstract

Electromagnetic fields were utilized for mixing of industrial solid and liquid phases which resulting in enhanced mass and heat transfer rates without the need to make other physical adjustments in set-up has been successfully experimented. This study reports on the application of super-imposed field (viz: Electric and Electromagnetic fields) so as to modify the transport Phenomena pertaining to solid-liquid contacting phases. Powdered solid and liquid have been taken between two electrodes in a specially designed cell which are electrically connected through suitable leads. Constant electric field strength has been applied across the electrodes, as a result of which the rate of movement of interface between the solid and the liquid has been analyzed, involving various systems. A correlation for the movement of interface has been developed which will act as a ready reckoner to find the values of time taken for the movement of interface.

Keywords: *Electric Field, Interface Movement, Field Strength, Electrodes.*

INTRODUCTION

Investigations on the application of electromagnetic or electric field (uniform field in particular) to solid-liquid contacting processes are almost absent in the past few decades, eventhough comparatively investigations on liquid-liquid systems are more. The contacting of solid and liquid in a large industrial tower can be taken as a case in point. The existing hydrodynamics could have already established certain flow patterns, resulting in a certain degree of mixing and mass/heat transfer. The application of this technique using an electromagnetic and electrical field would well result in augmenting, *in situ*, the mixing between solid and liquid phases increasing the mass /heat transfer rates, without the need to make other physical adjustments in the cell set-up.

It has already been indicated earlier that a super-imposed electromagnetic field can affect the mobility or the orientational characteristics of the subject molecules resulting in altered transport rates. The change in transport rate may be reckoned as partly due to the change (however small) effected on the potential equilibrium state itself by the super-imposed electromagnetic field or by the reduction or increase in the solid – liquid interfacial resistance to transport caused by molecular orientations and altered mobilities under the induced field, as well as by inducing and augmenting interfacial turbulence. It was with the idea of studying these effects that investigations were undertaken by Chandrasekharan *et al* (1970) and the author Chandrasekaran *et al* (1974), Cropper *et al* (1962) and Hill (1969) and further pursued by Mohan (1977). Mohan (1977), Holland (1966), Sjoblom *et al* (1966) and Pearce (1954) have studied mixing and mass

transfer in binary and ternary liquid-liquid systems. Dhanasekaran *et al* (1993) and Terasawa *et al* (1984) have studied mass transfer in gas-liquid systems. In the present study movement of interface and mass transfer in solid-liquid systems under applied electric fields are investigated.

A superimposed electromagnetic or induced electrical field on solid-liquid systems not only gives scope for developing techniques which may be of far reaching value in the control of transfer processes, but also finds application in biological and chemical systems and industrial unit operations in microgravity conditions.

Experimental Set-up and cell design
The experiment was envisaged with a specially designed cell which is a glass container and cylindrical in shape with funnel shaped arrangement on top. Inlet and outlet are in top and bottom side respectively through which the liquid inlet and discharged from the cell. Two adjustable disc shaped stainless steel electrodes inbuilt inside the cell and the interface distance between the electrodes can be adjusted to enable varying electromagnetic field strength. These circular discs whose diameters are slightly smaller than the inner diameter of the cell serve as plates to be electrified to provide the required electrical field between them. Electrical connection to the two plates is given through suitable leads brought out of the cell. The top of the cell is kept closed by a rubber cork to prevent evaporation of the liquid in the cell into the atmosphere and electromagnetic pellets placed inside the cell. A schematic diagram of the experimental set-up of this investigation is shown in Figure.1

Power Supply to cell
A Single phase Alternate current supplied to the cell through the transformer and the primary voltage to the cell is controlled in

primary circuit variance. The wattmeter assembly is used in this side for safety and to measure the supplied voltage in the primary side and the power strength is lowered in this side.
The transformer details are as follows:
Primary: 230 *V*, single phase, 50 *Hz*.
Secondary: 5000 *V*, single phase, 50 *Hz*.
Capacity: 500 *W*

Experimental Procedure
Movement of Interface
The movement of phases depends on the electrode distance and the rate of interfacial movement between solid-liquid system through the induced field strength of electric and electromagnetic system influenced by the distance between the electrodes, initially at 3 cm which is denoted by d_e. The movable electrode on the top side of the cell is to be adjusted to give applied potential of known value between the electrodes. The cell initially filled with solid powder of known height 1.5 to 1.6 cm the liquid medium is carefully poured in to the cell with slurry height to become 3 to 3.5 cm. The phase interface can present at center position of the solid – liquid slurry between the electrodes in the cell. A constant known induced field strength of E = 125 to 130 volts/cm, is applied. When the field is applied the interface is seen to get disturbed (The nature of the disturbance being dependent on the field applied and the system used) and then starts moving down. The rate of movement of the interface to different levels is followed by noting the corresponding time with the stop watch.

The rate of movement of through the electric and electromagnetic interface between solid and liquid is studied for the following chemical systems in acidic condition:

Salicylic acid	-	Ethanol
Citric acid	-	Ethanol
Benzophenone	-	Ethanol
Malic acid	-	Ethanol

Naphthalene   -   Ethanol
The interface movements, for each of the above systems are noted at applied voltages of 375 *V*, 562 *V*, 750 *V* and 937 *V* over 3 cm electrodes distance.

Results and Discussion
Movement of Interface between solid-liquid
The figure.2 shows the time t_x is plotted against interface level x (in cm) for the system Salicylic acid-Ethanol. It is observed for the system, the time t_x varies linearly with
level x. The time taken for the interface to move over levels 0.1, 0.2, 0.3 and 0.4 cm are found to be 220, 455, 702 and 960 seconds, respectively for an applied voltage of 375 *V* (electrode distance = 3 cm, and average field strength E = 125 *V*/cm). It is seen from the figure that t_x varies linearly with x. At applied electrical voltages of 375 (average field strength E = 125 *V*/cm) the slope is 2467 s/cm. The slopes recorded at applied voltages of 562, 750 and 937 are 2023, 1479 and 1144 s/cm respectively. It is seen that as the applied voltage is increased the movement of the interface is faster. Fig.3 to 6 show variation of time t_x with interface level x for the

systems mentioned above. The slopes at various applied voltages are shown.

The rate of interface movement for the system Benzophenone - Ethanol is the fastest, about 9 times when compared to the system Naphthalene - Ethanol, the slope being 1307 and 12024 s/cm respectively at applied voltage of 375. The investigation made to calculate the field strength and the movement of interface between the solid and liquid phases. It is assumed that the mixing takes place on both phases by application of induced field strength, the movement of both interface are opposite on the direction of mixing, which resulted homogeneity of phases.
Hence expressing m as a function of:
Density, ρ_2
Viscosity, μ_2
Acceleration due to gravity, g and
Diffusion coefficient, D_{12}
The application of dimensional analysis yields the functional relationship of the group $m(\mu_2 g/\rho_2)^{1/3}$ is plotted against the group $(\mu_2/\rho_2 D_{12})$ on log-log co-ordinates and from the slope and intercept of the (straight line) graph the values of β and α are obtained.
      The resulting correlation for the systems studied is given by

$$ m \left(\frac{\mu_2 g}{\rho_2} \right)^{1/3} = 1.7 \times 10^4 \left(\frac{\mu_2}{\rho_2 D_{12}} \right)^{3.05} \qquad (1) $$

Correlation for Movement of Interface
The interface movements and for the time taken is mainly dependents on so many variables in the system. The correlation and relationship between the variables such as A, E, d, x and the interfacial movement t_x with the physical properties are predicted through the dimensional analysis by some

assumption and function of assumed variables.
$f(t_x, g_c, d, A, d_e, x, E, \Delta_\rho, \mu_2, P, t_r) = 0$ (2)

Equation 2 may be transformed into the following dimensionless groups:

$$\left(\frac{t_x}{\sqrt{x/g_c}}\right) = C \left(\frac{Ad}{x^{5/2} d_e^{1/2}}\right)^{m_1} \left(\frac{t_r \, \mu_2^2}{PE^{1/2} \, \Delta\rho^3}\right)^{m_2} \left(\frac{\mu_2 \, t_r}{\Delta\rho \, x^2}\right)^{m_3}$$

(3)

where,
$m_1 = (C_1 C_2 / C_3^{1/2})$, $m_2 = (C_4 C_5 / C_6^2)$, $m_3 = C_7$, we get

This gives the form of the expression arising out of the functional relationship represented by equation 2.

However, it can be noticed that no term is present to take into account the dielectric properties ϵ_1 and ϵ_2, of the liquids, since they are dimensionless. Besides, as the interface moves and mixing takes place, the resultant changes in the effective dielectric constant of the two phases must be taken into account. In this present investigation the capacitors are considered series in the circuit and the whole system is considered as electric circuit with the electrodes parallel to the interface of the system. Considering C_1 is the capacitance of top layer and C_2 is the capacitance of bottom layer, then we can write an equation for effective capacitance as follows:

$$\frac{1}{C^*} = \frac{1}{C_1} + \frac{1}{C_2}$$

(4)

In terms of the area of surfaces of each of the phases, (which becomes single item, that is, the interfacial area, in the case of contacting phases), depth of each phase and permittivity of the phases, equation 4 can be rewritten as

$$\frac{d + d}{\epsilon^* \epsilon_0 A} = \frac{d}{\epsilon_1 \epsilon_0 A} + \frac{d}{\epsilon_2 \epsilon_0 A}$$

(5)

or

$$\epsilon^* = \frac{2 \epsilon_1 \epsilon_2}{\epsilon_1 + \epsilon_2}$$

(6)

and to predict the interfacial movement of solid – liquid system with varying dielectric constant of these both phases the above equation 6 is combined with equation 3 then the combined equation can be written as

$$\epsilon^* = \left(\frac{2\epsilon_1 \epsilon_2}{\epsilon_1 + \epsilon_2} \right) \frac{(d+x)}{d_e} \tag{7}$$

Addition of equation 7 into equation 3 yields the final form of the correlation as

$$\left(\frac{t_x}{\sqrt{x/g_c}} \right) = C \left(\frac{Ad}{x^{5/2} d_e^{1/2}} \right)^{m_1} \left(\frac{t_x \mu_2^2}{PE^{1/2} \Delta\rho^3} \right)^{m_2} \left(\frac{\mu_2 t_x}{\Delta\rho x^2} \right)^{m_3}$$

$$\left(\frac{2\epsilon_1 \epsilon_2}{\epsilon_1 + \epsilon_2} \frac{(d+x)}{d_e} \right)^{m_4} \tag{8}$$

A mathematical regression analysis using experimental data to eliminate statistically insignificant dimensionless groups from the correlation shows that equation 10 does not contain any such insignificant group. The generated data through dimensional analysis for the physical properties and variables are analyzed mathematically by using computer for predicting the values of exponents. The output values through the computer analysis as follows:

$m_1 = -0.69$, $m_2 = -0.36$, $m_3 = 0.61$ and $m_4 = 0.14$

The resulting correlation for the movement of interface can be written after the mathematical analysis as follows:

$$\left(\frac{t_x}{\sqrt{x/g_c}} \right) = 1.7 \times 10^7 \left(\frac{Ad}{x^{5/2} d_e^{1/2}} \right)^{-0.69} \left(\frac{t_x \mu_2^2}{PE^{1/2} \Delta\rho^3} \right)^{-0.36} \left(\frac{\mu_2 t_x}{\Delta\rho x^2} \right)^{0.61} \tag{9}$$

$$\left(\frac{2\epsilon_1 \epsilon_2}{\epsilon_1 + \epsilon_2} \frac{(d+x)}{d_e} \right)^{0.14} \tag{10}$$

This indicates that the effect of electric field strength is either to increase the rate of movement or to decrease the time taken for the movement of interface between the solid and liquid phase under induced electromagnetic field.

CONCLUSION
The result and reports on the variations of the application of electrical and induced electromagnetic fields to modify the transport and mass/heat transfer phenomena pertaining to solid-liquid contacting phases. The rates of movement of interface between

solid and liquid phase are studied involving various systems. A correlation for the movement of interface has resulted by means of induced field strength. The possible mechanisms have been discussed. As a long range of application, it may visualize when the biological and chemical transport rates could be controlled by using very low and tolerable electrical and electromagnetic potentials by using the specially designed mechanism.

List of Symbols and Abbreviations
Area of interface (or cross-sectional area of the cell), cm^2
$A.C$-Alternative current
C^*-Effective capacitance
C_1-Capacitance of the top layer
C_2-Capacitance of the bottom layer
d-Depth of the liquid taken, cm
D_{12}-Diffusion coefficient of solute (1) into solvent (2)
d_e-Distance between the electrodes, cm
E-Applied field strength, V/cm
E_1-Intensity of electric field for the solid (volts/cm)
E_2-Intensity of electric field for the liquid (volts/cm)
g-Acceleration due to gravity (cm/s^2)
g_c-Gravitational constant

$H.V$-High voltage
Hz-Herz
$K.V$-Kilo volt
m-Slope of t_x vs x
t_r-Relaxation time for the polar solute molecule, s.
t_x-Time taken for the movement of interface for any distance x, s.
P-Dipole moment of the polar solute molecule, Debyes
V',V-Applied voltage
W-Watts
x-Distance through which the interface has moved, cm

Greek Symbols
ϵ_1-Dielectric constant of the solid
ϵ_2-Electric constant of the liquid
ρ_2-Density of phase which acts us the solvent (gm/cc)
μ_2-Viscosity of the phase which acts as the solvent, gm/cm.s.
Δ_ρ-Difference in densities between the two phases, gm/cm^3

Subscripts
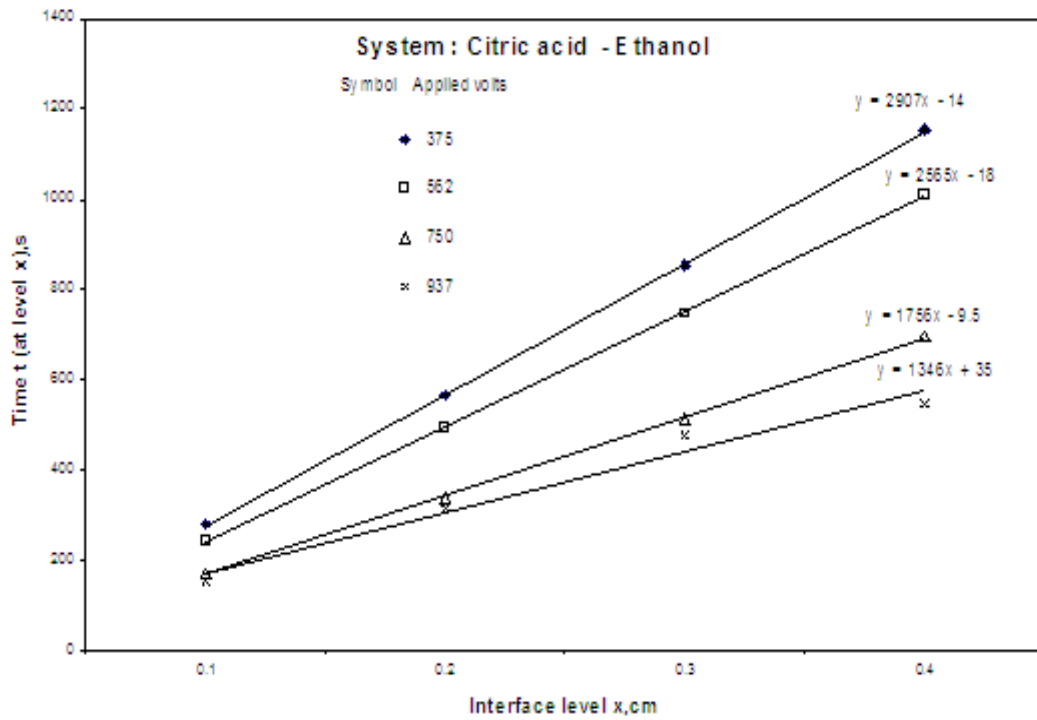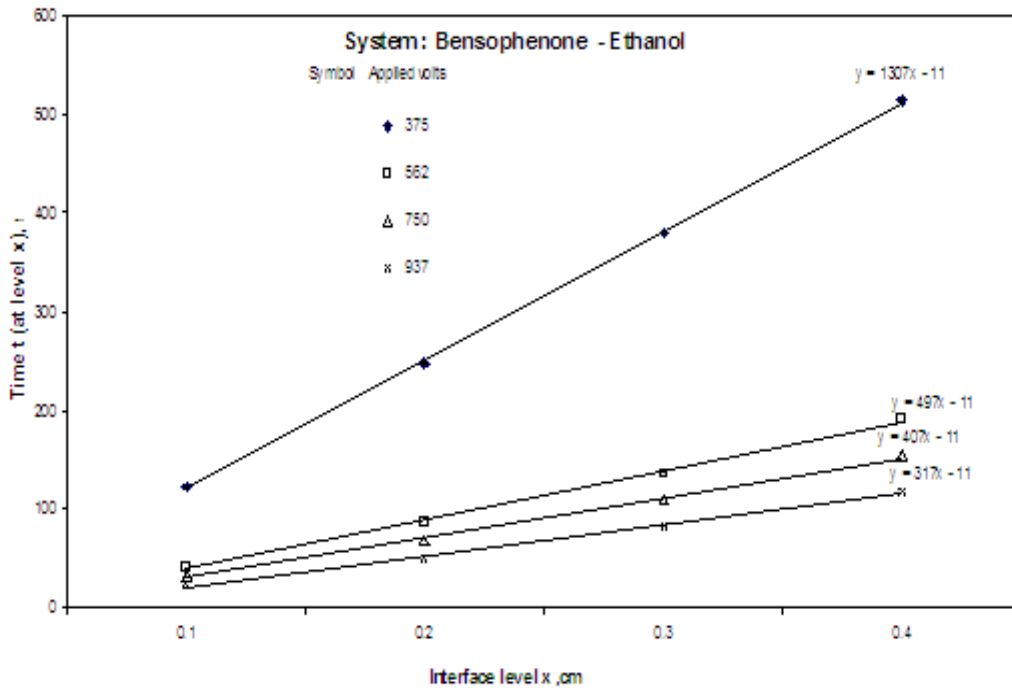e-Electrodes
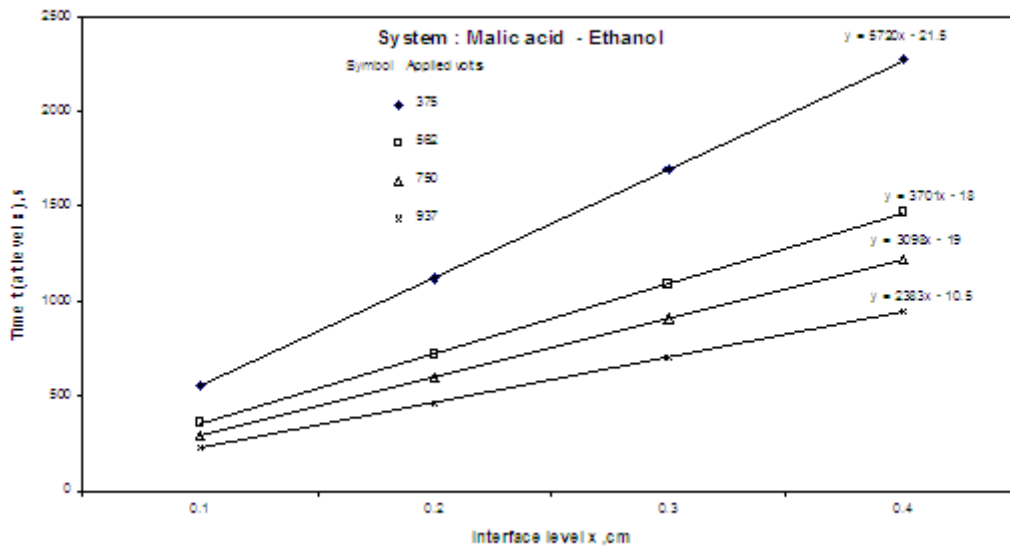r-Relaxation time
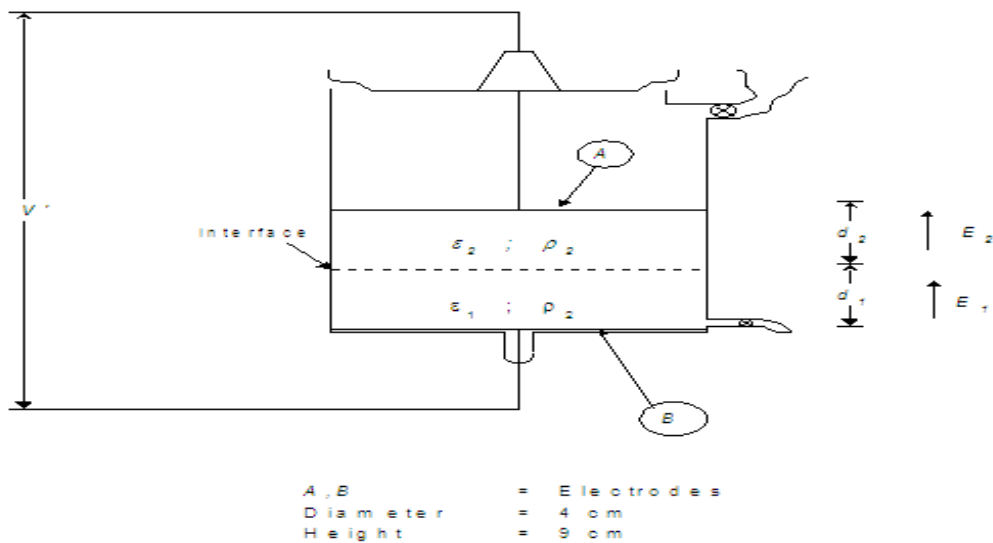
Fig.1 *Schematic diagram of the cell*
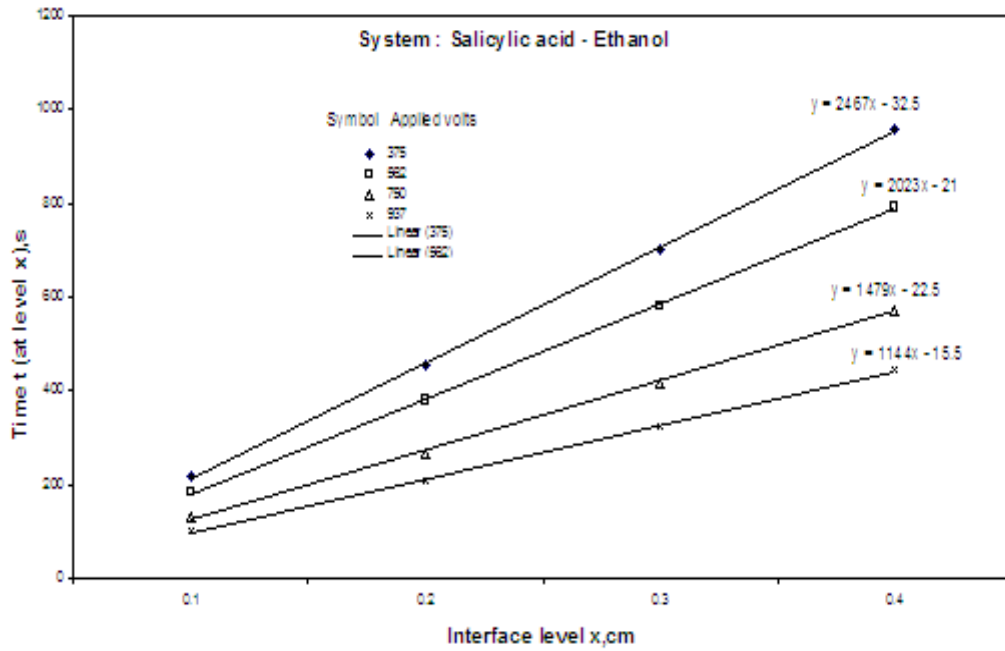
Fig.2 Movement of interface vs. Time with respect to varying field strength for Salicylic acid – Ethanol

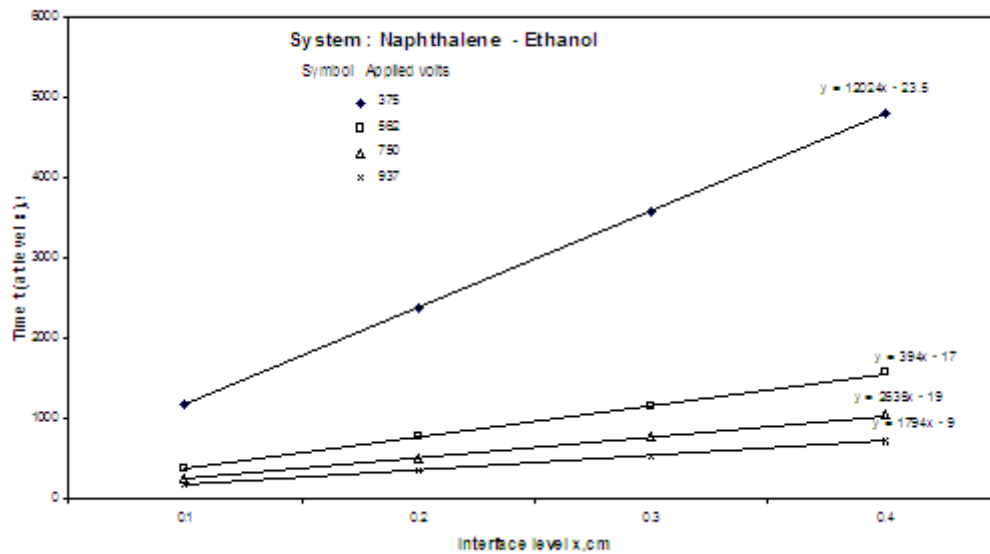*Fig.3 Movement of interface vs. Time with respect to varying field strength for Citric acid – Ethanol*

Fig.4 *Movement of interface vs. Time with respect to varying field strength for Benzophenone –*
Ethanol

Fig.5 *Movement of interface vs. Time with respect to varying field strength for Malic acid –*
Ethanol

Fig.6 *Movement of interface vs. Time with respect to varying field strength for Naphthalene – Ethanol*

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