PERGAMON International Journal of Heat and Mass Transfer 42 (1999) 1617–1632

International Journal of
HEAT and MASS
TRANSFER

Electroconvective heat transfer in a suspension of rod-like akageneite particle (β-FeOOH)

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Accepted in final form 28 July 1998

Abstract

The electroconvective heat transfer coefficient (EHTC) from experiments on colloidal suspension (rod-like akageneite particle (RLAP) (β-FeOOH) in distilled water) in a cylindrical enclosure is studied as a function of time, electric field, frequency, colloidal charge, concentration and orientation. The EHTC is strongly influenced by the charge and concentration of the colloidal particles. The EHTC data has been correlated by dimensional analysis. The data have been compared with the predicted correlations and are well correlated over the range of the Rayleigh number from 10^8 to 4.5×10^8. An empirical correlation relation has been proposed to evaluate the efficiency of convection (EOC) and the results for dc and ac fields are presented. © 1998 Elsevier Science Ltd. All rights reserved.

Nomenclature

A	surface area of the platinum wire
Cu	copper
d	diameter of the rod-like akageneite (β-FeOOH) particle
D	diameter of the cylinder
E_r	radial electric field
f_{el}	electrophoretic force
$FeCl_3$	ferric chloride
g	gravitational acceleration vector
Gr	Grashof number, $g\beta T_d D^3/\nu^2$
h_f	free-convective heat transfer coefficient
h_{el}	electroconvective heat transfer coefficient
I	current through the pt-wire in absence of U
I_{el}	current through the pt-wire in presence of U
IEP	isoelectric point
l	length of the rod-like akageneite (β-FeOOH) particle
L	length of the cylinder
Nu	Nusselt number, $h_f D/\lambda$
Nu_{el}	electric Nusselt number, $h_{el} D/\lambda$
n_p	number of akageneite particles/m^3
Pr	Prandtl number, ν/α
Pt	platinum wire
q	charge of the akageneite particle
Q_{el}	rate of heat transfer in presence of U
r_c	radius of the cylinder
R	resistance of the pt-wire
Ra	Rayleigh number, $(g\beta T_d D^3/\nu^2)Pr$
T_d	temperature difference between pt-wire and the surrounding medium
T_B	temperature of the surrounding medium
T_w	temperature of the pt-wire
U	voltage applied to the cylinder.

Greek symbols

α	thermal diffusivity
β	thermal expansion coefficient
β-FeOOH	akageneite particle
θ	angle of inclination from the vertical
ν	kinematic viscosity
μ	absolute viscosity
ρ	mass density
ε	permittivity of the fluid
λ	thermal conductivity
γ	efficiency of electroconvection.

1. Introduction

Heat transmission from heated bodies, mainly because of its great practical significance, has received con-

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PII: S0017-9310(98)00235-X

siderable experimental attention. An understanding of these processes is important in numerous devices and facilities needed for sustaining technological activities in space. It is also important for the understanding of heat transfer mechanisms on colloidal suspension in atmosphere or industrial applications [1]. Heat transfer on colloidal suspensions with charged particles may become important for space craft at a very high altitude, especially in the gravity-free environment [2].

Convection is the mode of heat transfer in fluid, a process whereby a moving fluid transfers heat from a surface. If the movement of fluid is natural, i.e., where movement is caused by density changes, the process is called 'natural convection'. If the movement of fluid is caused by a mechanical means, (e.g. a fan), the process is called 'forced convection'. Thus, there are various types of heat convection in gases and liquids such as free or forced convections, with either laminar or turbulent motion, and convection caused by electric and magnetic fields.

Natural convection of heat in a fluid often shows itself to be a relatively inefficient means of thermal transfer with many industrial processes using mixed convection or other outside body forces to make flows more turbulent. Therefore, the idea of imposing such constraints on thermal flows has the aim of enhancing mixing and thus heat transfer within the fluid. In particular, using electrical forces to this end is referred to as electro-thermohydrodynamics (ETHD). Work on this subject dates back to the mid-1930s with Senftleben and Braun's experiments using gases [3] and then those of Ahsmann and Kronig [4] in 1950 on liquids. In the last 35 years, development of this topic has continued and there is a large amount of published work dealing mainly with the application of electric and magnetic fields in gases and liquids. Interest has recently been stimulated to study the electroconvection in colloidal particles in the body of a carrier liquid. The various characteristics of these particles such as their physicomechanical, electrophysical and thermophysical properties can be determined using electric fields. Colloidal particles find use in the solution of many technical problems such as sealing, lubrication, detection of heat transfer and damping problems. Additionally, devices incorporating colloids have found applications in high-vacuum equipment, LASER systems, computers, material separation, domain detection and many other areas [5–10]. In order to select the optimum regimes for the construction of these equipment and to determine the most effective heat transfer conditions and characteristics of fluid disperse heat carriers, it is necessary to know how electric fields influence the processes of momentum and thermal energy transfer in such systems.

The present work was undertaken with the aim of studying thermo-physical properties as well as the laws governing the EHTC of colloidal suspension in a cylindrical enclosure. The properties of these suspensions experience a sharp change in the presence of non-uniform electric fields. Thus, for example, the EHTC for surface charged particles is increased by several orders of magnitude when an electric field is applied.

In the present work the result of the EHTC of RLAP (β-FeOOH) suspension in distilled water is being reported. The EHTC has been evaluated under the influence of ac and dc fields, with particular choice given to an ac field. The effect of particle concentration and particle surface charge on the EHTC are studied. Additionally, the EHTC data have been correlated by dimensional analysis. The data have been compared with the empirical correlation relation and analytical expression and is well correlated over the range of the Rayleigh number from 10^8 to 4.5×10^8. An empirical correlation relation has also been proposed to evaluate the EOC and the results for dc and ac fields are presented.

As mentioned above, the results of this study may find application in several areas of industry and technology. An important area in mind is space technology, especially in a gravity-free environment. Here, the investigated parameters are expected to behave differently, since in gravity-free space the particles are disturbed randomly and uniformly due to thermal motion. As the electric field is applied, each neutral particle becomes a dipole with an induced dipole moment. The higher the applied field, the stronger the dipole–dipole interaction among the particles. The competition between the dipole–dipole interaction and thermal motion may lead to several interesting phenomena, such as induced phase transitions and the formation of single chains or aggregate of chains to form thick columns. Furthermore, the presence of particles carrying a charge in such an environment may lead to several other consequences.

2. Experimental

The detailed experimental arrangement used in this investigation has been given elsewhere [11–14], however, a brief description of the equipment is furnished here.

The EHTC data was evaluated from a hot wire cell made from a copper cylinder (diameter = 53 mm) with a fine platinum wire (diameter = 0.025 mm) stretched along its axis. The hot wire cell in series with a standard resistor was placed into one arm of a Wheatstone bridge. The electric field was applied between the cylinder and the wire which was earthed. The heating current was supplied from a constant current source, while the surrounding temperature was maintained constant in a constant temperature bath. The EHTC data was obtained by calibrating the wire as a platinum resistance thermometer and then measuring the voltage across it and a standard resistor in series with it. If I is the current flowing through the wire in the absence of any electric field and I_{el} is the additional current necessary to keep the bridge balanced in the presence of any electric field, then the rate of heat transferred is given by

$$Q_{\mathrm{el}} = (2II_{\mathrm{el}} + I_{\mathrm{el}}^2)R$$

where R is the resistance of the pt-wire. The EHTC is then obtained by using the relation

$$h_{\mathrm{el}} = \frac{Q_{\mathrm{el}}}{AT_{\mathrm{d}}}$$

where A is the surface area of the wire and T_{d} is the temperature difference between the wire and the surrounding medium.

The RLAP (β-FeOOH) particles (0.20×0.03 μm) used in this investigation were prepared by forced hydrolysis of ferric chloride ($FeCl_3$) solutions [15, 16]. A transmission electron micrograph of these particles is presented in Fig. 1. The isoelectric point (IEP) of such particle was at pH 7.1. The density of these particles was at 5.20 gm/cm^3 and the specific magnetic moment was at 0.1 0_e cm^3 g^{-1}. Unless stated otherwise, all measurements were carried out at a fixed particle concentration of 2.2×10^9 particles/cm^3 and pH value 11. The particles used in this investigation are known to be negatively charged. Thus at higher pH values, the interparticle repulsion prevents the particle agglomeration, coagulation, settling, etc, and the suspension remains stable over a longer period of time. The additives are used only to charge the particles and the heat transfer properties are evaluated at various charge states of the colloidal suspension.

In order to test the experimental setup, the experiment was carried out in distilled water in the absence of an electric field. The free-convective heat transfer coefficient h_{f} was determined for various heating currents. The global effect of convective heat transfer is written in terms of the Nusselt number Nu, which is the ratio of the mean heat flux to the heat flux which would exist without convection for the same temperature difference

$$Nu = \frac{h_{\mathrm{f}}D}{\lambda} \tag{1}$$

The Nusselt number Nu is normally plotted as a function of the Rayleigh number Ra (proportional to the temperature difference)

$$Ra = \frac{g\beta T_{\mathrm{d}}D^3}{\nu^2}Pr \tag{2}$$

where β is the coefficient of thermal expansion of the liquid and g is the gravitational acceleration and Pr is the Prandtl number. The value of Nu as a function of Ra (for non-applied electric field) is evaluated for distilled water and they agree very well with the already known results [17]. The good agreement between our experimental results and the classical ones constitutes a test for our experimental setup.

3. Results and discussion

3.1. Convection in distilled water

Convection in distilled water is measured under the influence of ac and dc fields and for various pH values.

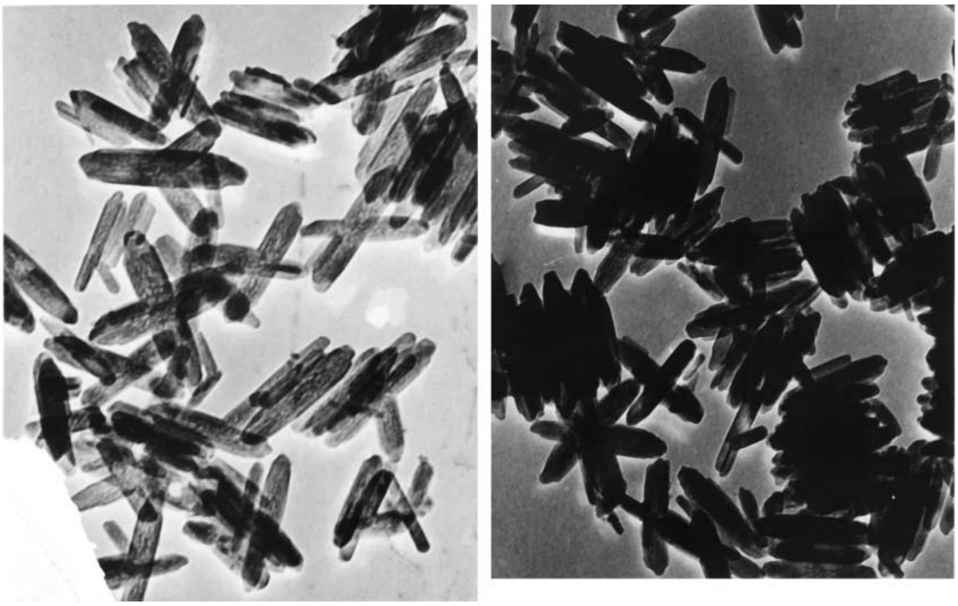


Fig. 1. A transmission electron micrograph of RLAP (β-FeOOH) used in the convection experiment. 1: Length, $l = 0.20$ μm; diameter, $d = 0.03$ μm.

The pH of the distilled water was changed by adding NaOH. The behaviour of EHTC observed under the influence of the dc field is shown in Fig. 2a, while the trend observed under the influence of the ac field is shown in Fig. 2b. The effect of additives on EHTC are indicated in various curves. Clearly, there exists a critical electric field ($\cong$ 0.5 V) below which no convection is observed. As the field is increased gradually, the EHTC increases extremely slowly, and the increase is also slow for pH values largely different from IEP (curves 2 and 3 in Fig. 2b). For pH values close to IEP, the change in EHTC is almost close to zero, as indicated by curve 1 in Fig. 2b. In the case of a dc field, the EHTC decreases gradually as the field is increased. The EHTC is negative, and the negative behaviour implies a suppression of the free-convection by electroconvection.

3.2. Convection in colloidal suspension (RLAP (β-FeOOH) in distilled water)

3.2.1. Time evolution of electroconvection

The time evolution of electroconvection for RLAP (β-FeOOH) suspension in distilled water is presented in Fig. 3. As seen in the figure, the EHTC exhibits a 'timing' effect. The magnitude of the convection decreases with time. The decrease is significant only within the first few minutes after the field is applied, followed by a very slow decrease after 10 min to reach a stationary value in about

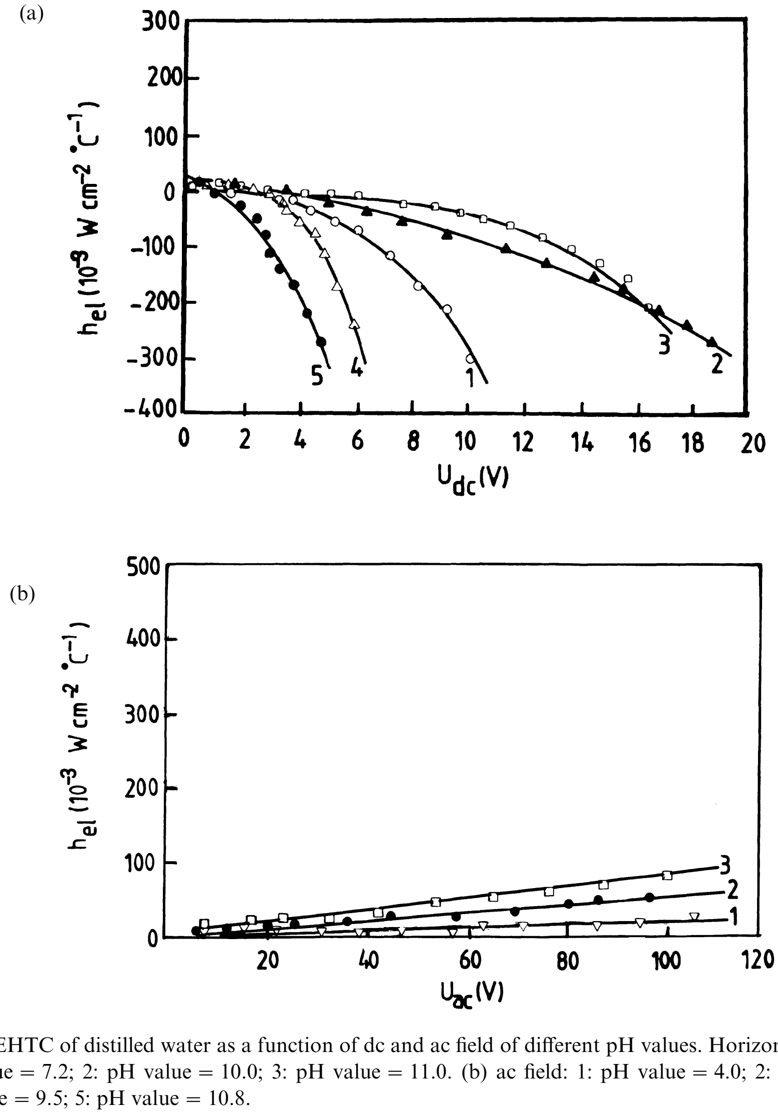


Fig. 2. Dependence of EHTC of distilled water as a function of dc and ac field of different pH values. Horizontal cylinder, $T_d = 14°C$. (a) dc field: 1: pH value = 7.2; 2: pH value = 10.0; 3: pH value = 11.0. (b) ac field: 1: pH value = 4.0; 2: pH value = 5.40; 3: pH value = 7.8; 4: pH value = 9.5; 5: pH value = 10.8.

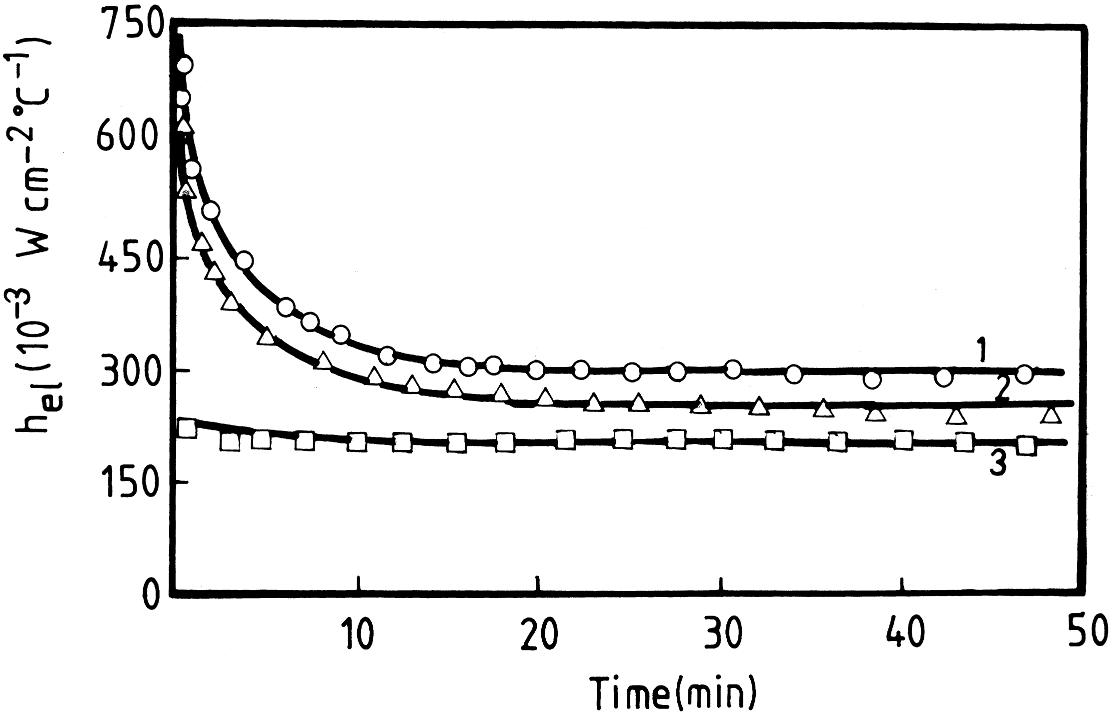


Fig. 3. Time evolution of EHTC of RLAP (β-FeOOH) suspension in distilled water. Horizontal cylinder, $T_d = 8.5°C$. 1: $E = 0.1$ V dc, pH value = 11.0; 2: $E = 0.1$ V dc, pH value = 11.0 obtained after 48 h; 3: $E = 60$ V ac, 60 Hz, pH value = 5.20.

30 min. A similar trend was noticed when the measurement was done after 48 h (curve 2, Fig. 3). The initial rapid decrease in EHTC may be attributed to relaxation phenomena. Before the application of the electric field, the particles are randomly distributed in carrier liquid and experience no collision with each other. Since the particles are charged, once the electric field is turned on, they undergo collisions with each other until thermal equilibrium is achieved. The presence of collisions reduces the EHTC due to reduction in particle momentum. The collision probability reduces gradually with time until thermodynamic equilibrium is achieved with the surroundings. Thus the EHTC reduces gradually and remains practically constant over a while.

The pH of the suspension changes gradually with time, which in turn causes the reduction in the surface charge of the particles. Thus, the ‘aging’ effect is associated with the particle settling, coagulation, etc, as clearly noted in curve 2 of Fig. 3. It is expected that the surface charge of the colloidal particles is playing a dominant role in the convective heat transfer mechanism.

Time dependence was also investigated under the influence of an ac field of frequency 60 Hz and a colloidal solution of pH value 5.20. No change in EHTC was observed with time during which ac field was applied (see curve 3 of Fig. 3).

3.2.2. Effect of dc fields on convection

Figure 4 presents measured EHTC data for colloidal suspension ((RLAP (β-FeOOH) in distilled water)) obtained under conditions of variable dc fields and pH values. The EHTC increases with a slight increase in fields and reaches a maximum after about 0.1 V. The increase is extremely significant for pH values largely different from IEP (curves 1, 4, 5 and 6). The EHTC then decreases rapidly to zero as the field is increased and then becomes negative, implying a suppression of the free convective heat transfer coefficient. The EHTC decreases further but gradually as the field strength is increased.

The electric force which acts on fluid per unit volume is expressed as follows [18]

$$fe = q\bar{E}_r + \mathrm{grad}\left(\frac{1}{2}\bar{E}_r\rho\frac{\partial\varepsilon}{\partial\rho} + \frac{1}{2}\right)\bar{E}_r^2\,\mathrm{grad}\,\varepsilon \tag{3}$$

where the first term represents the Coulomb force or the electrophoretic force (EF) and the last two terms represent forces induced by the non-uniformity of the dielectric constant. In the present investigation, a suspension of charged particles is considered. The contribution to the EHTC arises mainly due to EF. The EF on the colloidal fluid can be written as

$$f_{el} = qE_r n_p \tag{4}$$

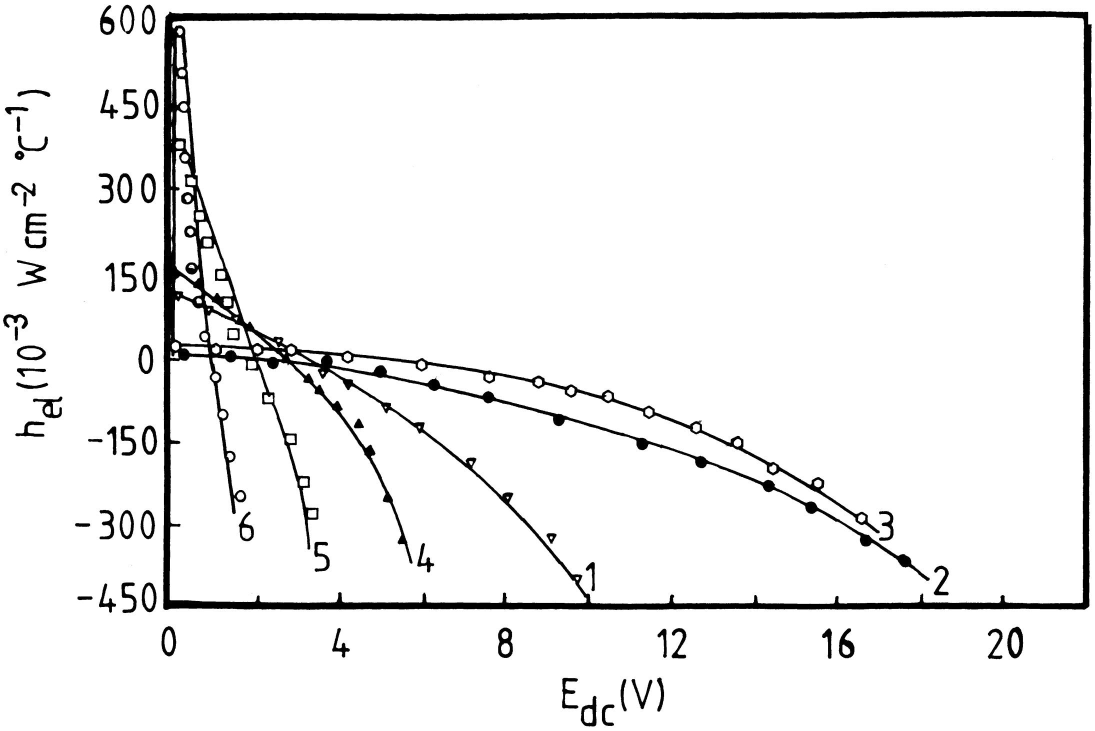


Fig. 4. Dependence of EHTC of RLAP (β-FeOOH) suspension in distilled water as a function of dc field with different pH values. Horizontal cylinder, $T_d = 12^\circ C$. 1: pH value = 4.0; 2: pH value = 5.40; 3: pH value = 7.50; 4: pH value = 9.0; 5: pH value = 10; 6: pH value = 11.0.

where q is the charge of the colloidal particle, n_p is the number of particle per unit volume and E_r is the radial electric field intensity. The radial electric field intensity is estimated as

$$E_r = \left(0.13\frac{U}{r}\right)(\text{V/cm}) \tag{5}$$

where r is the distance from the centre of the platinum wire and U is the voltage applied to the cylinder. The total number of colloidal particles in the cylinder is given by

$$n_p = \pi r_c^2 L n_p \tag{6}$$

where r_c is the radius of the cylinder and L is its length.

As the field is turned on, the EHTC increases extremely quickly until the field is of the order of 0.1–0.2 V when the density inversion occurs (the number of particles per unit volume decreases). Since the cylinder is maintained at positive potential and for highly negatively charged particles (largely different from IEP), the EF rises up suddenly to a very high level when the field is applied. Thus, the EHTC increases almost vertically near the vicinity of the origin. The maximum increase in EHTC is reduced gradually as the charge of the particles is reduced. Near the IEP, the increase in EHTC is practically zero due to absence of charges (curves 2 and 3). It turns out that the charge of the colloidal particles are playing a dominant role in the energy transfer mechanism.

On further increase in electric field, the EHTC drops down rather quickly and approaches a zero value. The reduction in EHTC observed in this case is associated with the number of particles involved in the energy transfer mechanism. As the total number of particles n_T is fixed, the number of particles present in the fluid medium will decrease gradually with increase in electric field, causing a reduction in EHTC. As the field is further increased, EHTC approaches a zero value, implying a complete removal of the charged particles from the fluid medium ($n_T \to 0$). On further increase in electric field, it becomes negative and follows the trend as observed in distilled water.

3.2.3. *Effect of ac fields and frequency on convection*

Figure 5 presents measured EHTC data for variable ac fields and pH values, above and below IEP. A sharp rise in EHTC is observed for pH values largely different from IEP (curves 4, 5, 6 and 7), whereas the EHTC changes very slowly and gradually for pH values close to IEP (curves 2 and 3). The negligible change in EHTC presented in curve 1 resulted from the polarity effect.

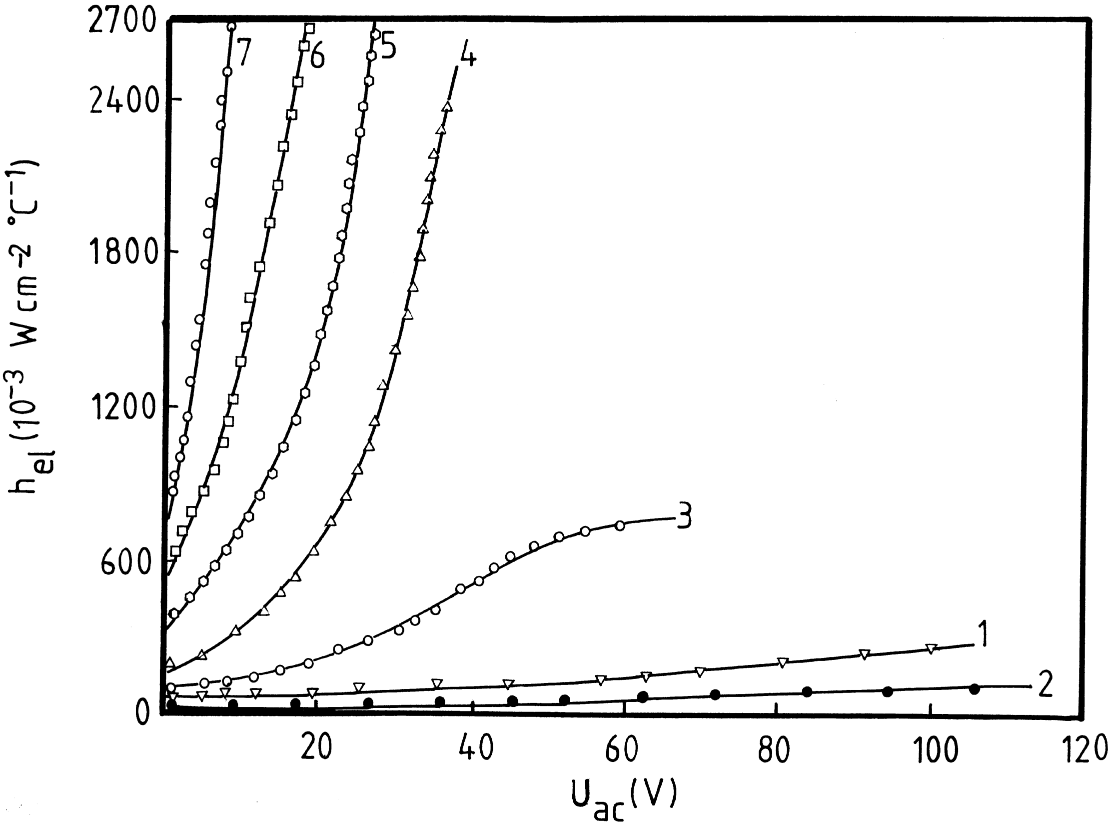


Fig. 5. Dependence of EHTC of RLAP (β-FeOOH) suspension in distilled water as a function of ac field with different pH values. Horizontal cylinder, $T_d = 11.0$°C. 1: pH value = 4.0; 2: pH value = 7.40; 3: pH value = 9.0; 4: pH value = 9.70; 5: pH value = 10.0; 6: pH value = 10.70; 7: pH value = 11.30.

When an ac electric field, frequency of which is 60 Hz is applied to a fluid, the EF is negligible because the electric relaxation time of most fluids is of the order of 10–100 s. For a charged suspension, EF is found to be significant even in an ac field, and the EHTC rises extremely quickly for pH values largely different from IEP. However, for pH values close to IEP, the surface charges of the particles are negligible leading to negligible change in EHTC.

The magnitude of the EHTC decreases gradually as the frequency of the applied field is increased (Fig. 6a). It has been observed that the polarization of the molecule in an ac field is less than that in a dc field [19]. Thus, the dielectrophoretic forces (DF) should also be less in the former field and consequently, the EHTC in the presence of ac fields would be less than that due to dc fields. The polarization of the molecules in the presence of an ac field will decrease gradually as the frequency of the field is increased. As a result, DF would decrease, leading to reduction in EHTC.

The EHTC data were also collected at higher frequencies (up to 1 KHz), and the results are presented in Fig. 6b. As seen in the figure, EHTC decreases with frequency, reaches a minimum value and then increases again as the frequency is increased. The decrease in EHTC with increase in frequency is due to polarization effect as explained above. However, the increase in EHTC with increase in frequency may be associated with the stirring effect of the ac field. As the frequency of the ac field is increased, the vibrations generated by the ac field also increases, leading to an increase in EHTC with increasing frequency. From the results, it is concluded that an energy absorption in the dielectric constant takes place in the frequency range where EHTC attains a minimum value.

3.2.4. Effect of pH values on convection

Figure 7(a, b) shows the dependence of EHTC on pH values at a fixed dc ($U = 0.1$ V) and ac ($U = 8.0$ V) fields. As observed in both cases, the change in EHTC is negligible for pH values close to IEP, and for pH values less than IEP. However, the change in EHTC is significant for pH values greater than IEP, and changes extremely significantly for pH values largely different

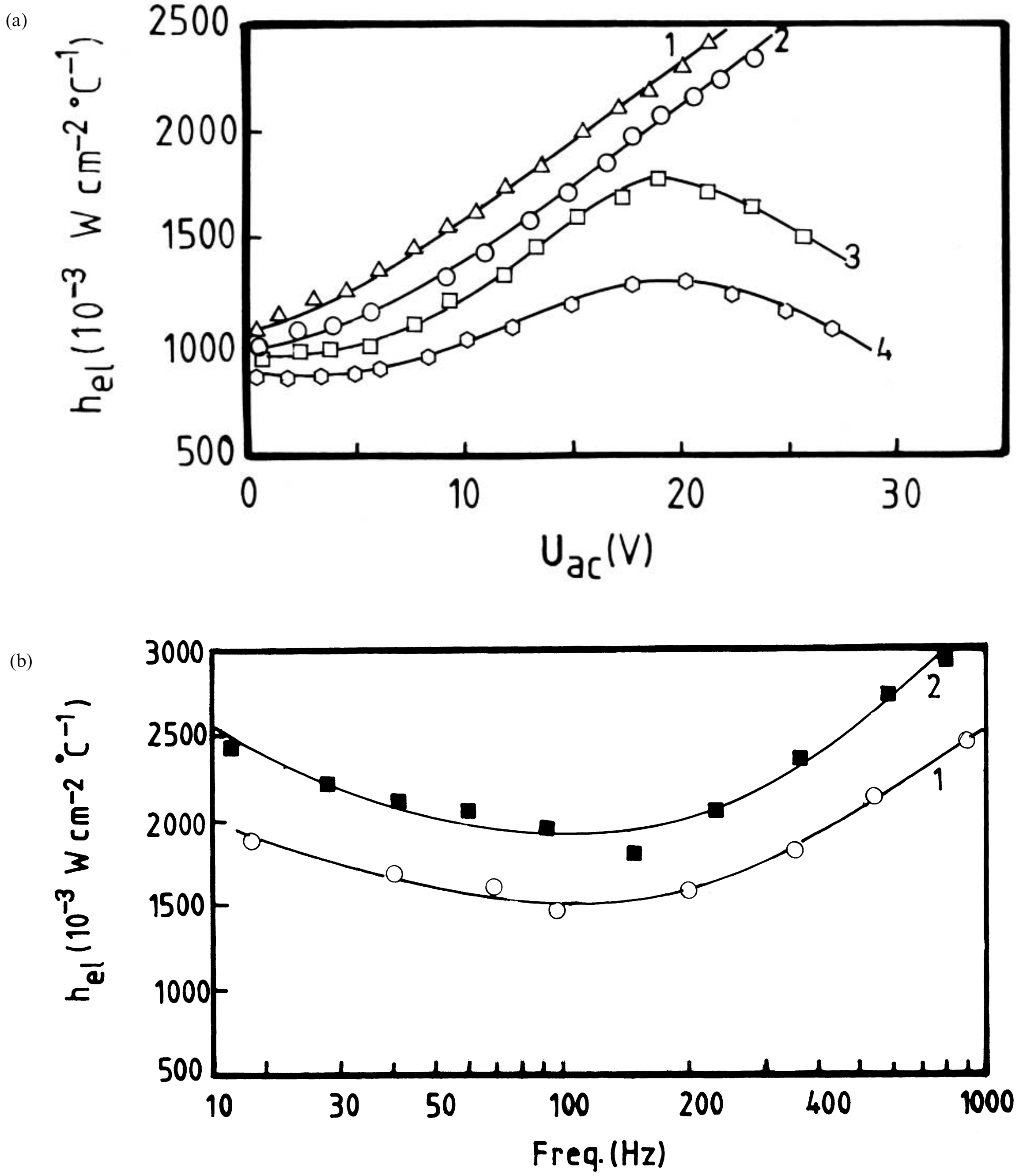
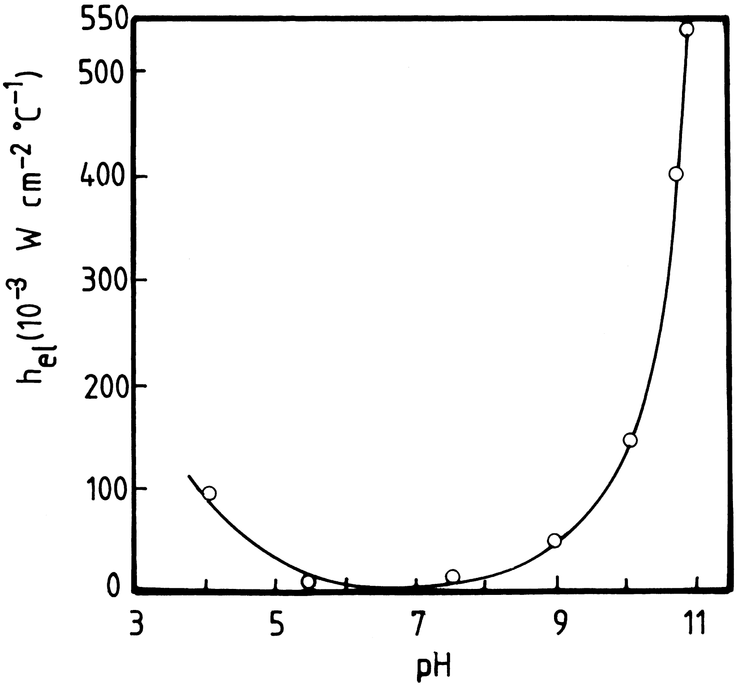


Fig. 6. (a) Dependence of EHTC of RLAP (β-FeOOH) suspension in distilled water as a function of ac field with different frequency (f). Horizontal cylinder, pH value = 11.0. 1: $T_d = 7.0$°C, $f = 60$ Hz; 2: $T_d = 5.0$°C, $f = 60$ Hz; 3: $T_d = 7.2$°C, $f = 120$ Hz; 4: $T_d = 7.10$°C, $f = 200$ Hz. (b) Dependence of EHTC of RLAP (β-FeOOH) suspension in distilled water as a function of frequency with fixed ac field. Horizontal cylinder, pH value = 11.0, $T_d = 7.5$°C. 1: $U = 15$ V ac; 2: $U = 30$ V ac.

from IEP. The reason is that at pH close to IEP, the surface charge of the particles are almost zero, leading to a negligible change in EHTC. For pH values less than IEP, the particles are positively charged, while the cylinder is also maintained at a positive potential. As a result, EHTC decreases due to polarity effect. For pH values greater than IEP, the particles are negatively charged and as a result, the EHTC increases extremely

(a)



(b)

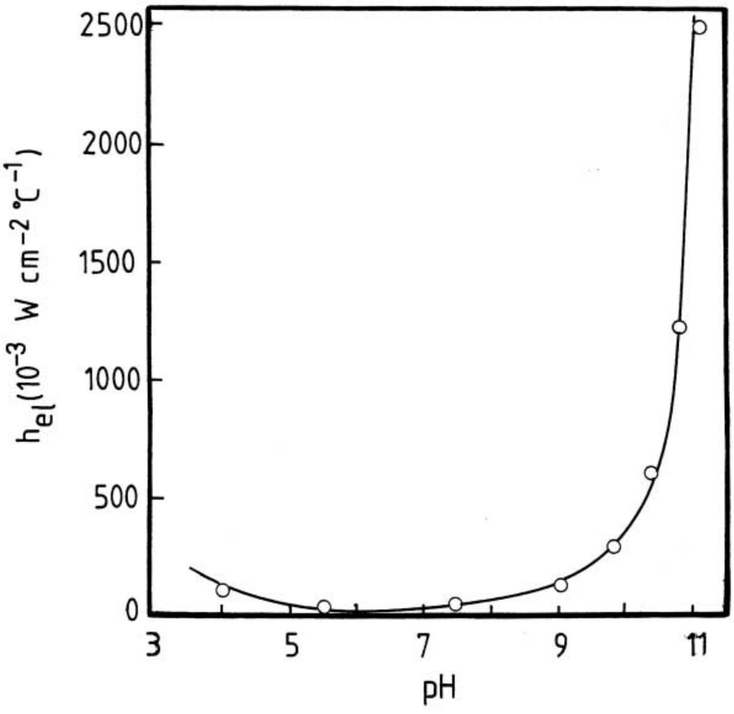


Fig. 7. Dependence of EHTC of RLAP (β-FeOOH) suspension in distilled water as a function of pH value. Horizontal cylinder. (a) $E = 0.10$ V dc, $T_d = 12$°C; (b) $E = 8$ V ac, $T_d = 11$°C.

quickly due to increased EF. The increase is almost vertical for pH values close to 11. The phenomena is attributed to 'charge effect'!

3.2.5. Effect of suspension concentration on convection

In Fig. 8 the results of the study concerning the effect of an ac field on EHTC for different particle concentrations is presented. It is found that EHTC increases with increased particle concentration. This phenomenon may have occurred because, when the concentration of the suspension is increased, the particle number in the fluid medium also increases. As a result, EF acting on the particle increases and this, in turn, enhances EHTC.

3.2.6. Effect of cylinder orientation on convection

The effect of cylinder orientation on EHTC for RLAP (β-FeOOH) suspension in distilled water is presented in Fig. 9. In the absence of any electric field, the free-convective heat transfer coefficient always decreases as the cylinder is moved from horizontal to vertical position [20]. A similar effect is also noticed in RLAP (β-FeOOH) suspension in distilled water (curve 1). An increase in concentration of the suspension increased the magnitude of the EHTC, but the trend for increased inclination remains the same (curve 2). However, in presence of the electric field, an increase in EHTC is noticed as the inclination of the cylinder is increased. The increase is significant for inclination greater than about 50° and becomes maximum when the cylinder is kept in a vertical position (curves 3, 4, 5, 6 and 7). The trend for increased inclination increases with an increase in T_d (curves 4 and 5) and also with U (curves 4 and 6), and increases extremely significantly for pH values largely different from IEP (curves 4 and 7).

The difference in EHTC between horizontal and vertical cylinders is presented in Fig. 10 where curve 1 is for the horizontal cylinder, while curve 2 is for the vertical cylinder. As seen in the figure, the EHTC for the vertical cylinder is found to be higher than the horizontal cylinder. The difference in the two cases may be due to the gravitational effect. In the horizontal position, the gravitational effect is non-symmetrical with respect to each half of the fluid separated by the platinum wire. In the upper half of the fluid, the hot volume of the liquid is moving in the upward direction, while the gravity acts

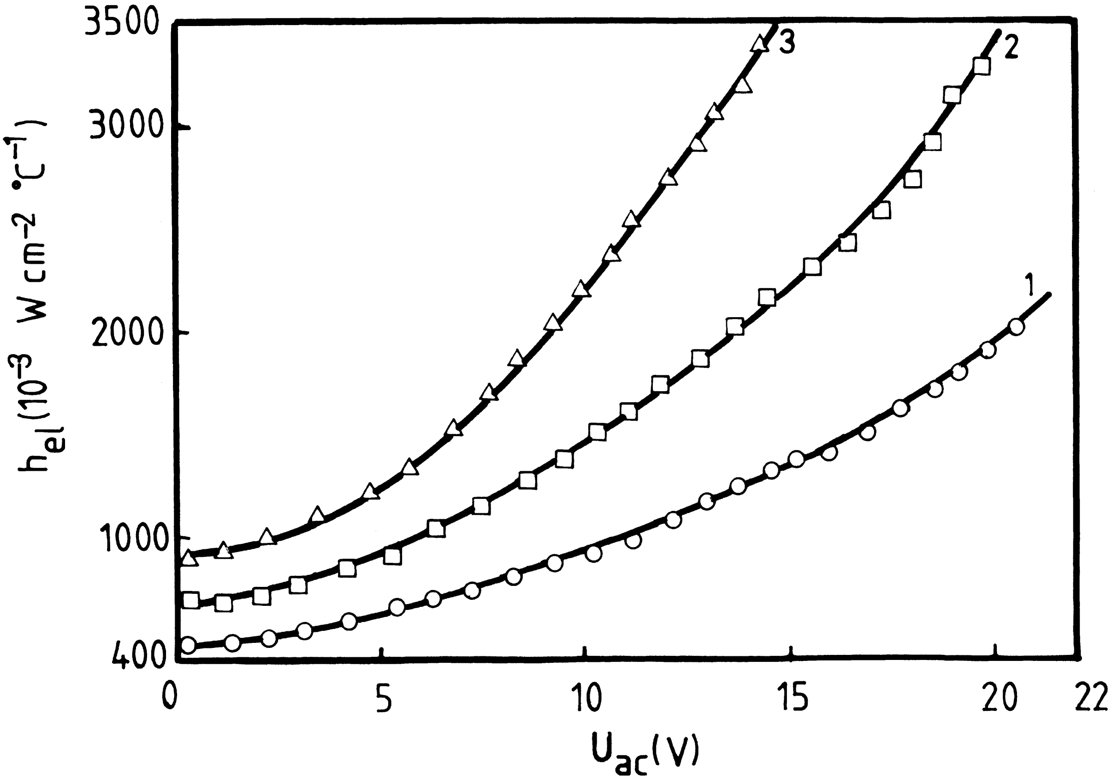


Fig. 8. Dependence of EHTC of RLAP (β-FeOOH) suspension in distilled water as a function of ac field with different colloidal concentrations. Horizontal cylinder, $T_d = 8°C$. 1: $n_p = 2.2\times10^{15}$ particles/m^3; 2: $n_p = 4.4\times10^{15}$ particles/m^3; 3: $n_p = 6.6\times10^{15}$ particles/m^3.

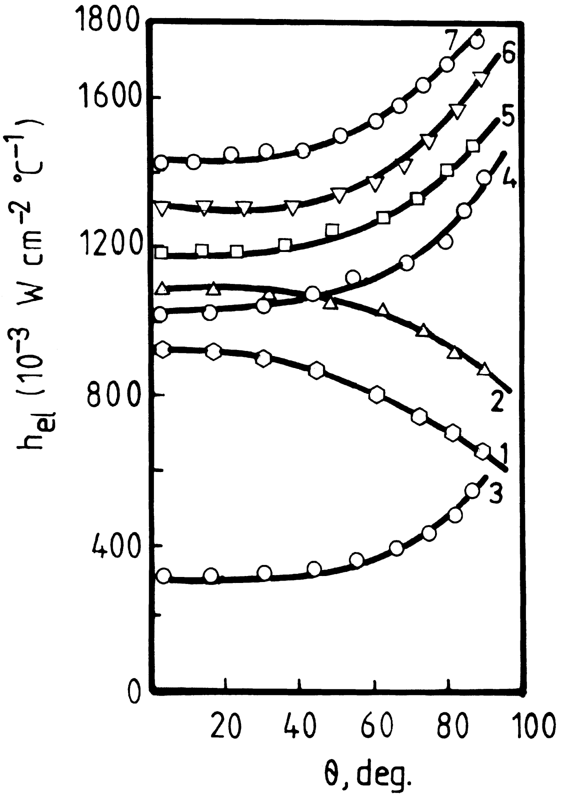


Fig. 9. Effect of inclination to the horizontal on the EHTC from a cylinder in RLAP (β-FeOOH) suspension in distilled water. pH value = 10.60 (1–6). 1: h_f, $T_d = 10°\text{C}$, $n_p = 1.1 \times 10^{15}$ particles/m^3; 2: h_f, $T_d = 10.10°\text{C}$, $n_p = 2.2 \times 10^{15}$ particles/m^3; 3: h_{el}, $T_d = 9°\text{C}$, $E = 0.1$ V dc, $n_p = 1.1 \times 10^{15}$; particles/m^3; 4: h_{el}, $T_d = 10.1°\text{C}$, $E = 7$ V ac, $n_p = 2.2 \times 10^{15}$ particles/m^3; 5: h_{el}, $T_d = 14°\text{C}$, $E = 7$ V ac, $n_p = 2.2 \times 10^{15}$ particles/m^3; 6: h_{el}, $T_d = 10°\text{C}$, $E = 10$ V ac, $n_p = 2.2 \times 10^{15}$ particles/m^3; 7: h_{el}, $T_d = 10.15°\text{C}$, $E = 7$ V ac, $n_p = 2.2 \times 10^{15}$ particles/m^3; pH value 11.30.

downwards. Consequently, while the hot volume of the liquid is moving in the downward direction, gravity enhances its flow. The net effect is that the EHTC in a horizontal cylinder is reduced as compared to a vertical cylinder where the gravity acts symmetrically with respect to the platinum wire which is mounted along the cylinder axis. Thus, the EHTC is reduced when the cylinder is kept in a horizontal position.

3.2.7. *Efficiency of convection (EOC) in presence of electric field*

The efficiency of free-convection has been defined as transforming the rate of electrical power supplied to the system into the rate of generation of kinetic energy of convective motion [21]. In the present study, the view was taken so that the measured EHTC in the presence of an electric field represented a useful conversion of additional electrical energy into the rate of generation of the kinetic energy of convective motion. In the presence of an electric field, the EOC can be calculated using

$$\gamma = \frac{h_{el}}{h_{el} + h_f} \tag{7}$$

where h_f is the free-convective heat transfer coefficient and h_{el} is the electroconvective heat transfer coefficient. The EOC for a RLAP β-FeOOH suspension in distilled water is presented in Table 1 (dc field). The results for distilled water and RLAP (β-FeOOH) suspension in distilled water is presented in Table 2 (ac field). In each case, the EOC has been calculated for various pH values largely different from IEP. In the case of dc field, a sharp rise in efficiency is observed at very weak field strengths and at pH values largely different from the IEP. As the field is further increased, the efficiency approaches a zero value and then becomes negative. A zero value of efficiency implies a complete removal of the charge particles from the carrier liquid, while a negative value implies a suppression of the free-convection by electroconvection. The negative behaviour of γ is similar to that observed in the carrier liquid only. The maximum efficiency obtained in a dc field is 67%, corresponding to a pH value of 11.0 and an electric potential of 0.1 V, while an efficiency of 54% corresponds to an electric potential of 0.08 V. A sharp rise in efficiency is also observed in ac fields, but in slightly larger fields. More significantly, the efficiency increases extremely quickly when the surface charge of the colloidal particles is increased. The sharp rise in efficiency at higher pH values is thus attributed to a charge effect. For a higher surface charged particle (pH = 11.30), an efficiency of 53% is obtained at an electric potential of 5 V, while the maximum efficiency (72%) corresponds to an electric potential of 12 V. Thus, the electric potential required for an ac convection is roughly 63 times large than the dc convection, and this is due to relaxation phenomena associated with the ac field.

4. Working correlations for electroconvection

One of our primary objectives is to find a relationship between the dimensionless quantities of Nusselt and Rayleigh numbers, and an appropriate geometric parameter. The mean Nusselt number and Rayleigh number are defined by

$$(Nu_{el})_D = \frac{h_{el}D}{\lambda} \tag{8}$$

$$Ra_D = \frac{g\beta T_d D^3}{\nu^2} Pr \tag{9}$$

where D is the diameter of the cylinder and λ is the

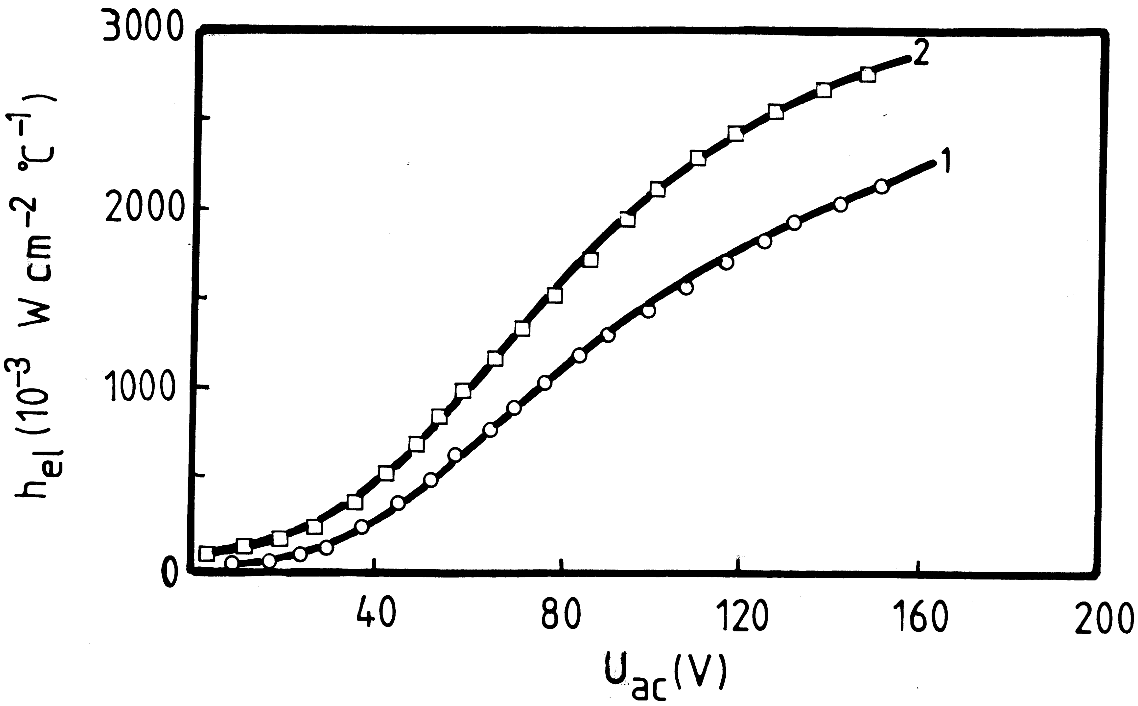


Fig. 10. Dependence of EHTC of RLAP (β-FeOOH) suspension in distilled water as a function of ac field in horizontal and vertical cylinders. pH value = 9.0. 1: horizontal cylinder, $T_d = 9.20°C$; 2: vertical cylinder, $T_d = 9.10°C$.

thermal conductivity of the fluid. The fluid properties were evaluated at the film temperature given by

$$T_f = \frac{T_w + T_B}{2} \tag{10}$$

where T_w is the temperature of the wire and T_B is the temperature of the surrounding medium.

Many previous analysis [22–24] of the enclosure free-convective heat transfer data have shown that correlations of the form

$$Nu_L = C_1 Ra^{C_2} \tag{11}$$

could correlate extremely well with vertical cylindrical data and plates. Experimental correlations of heat transfer data for air as the test fluid reported by Warrington and Powe [25] are given by

$$Nu_L = 0.479 Ra_L^{0.171} \tag{12}$$

In the present study, the EHTC is described in terms of the average Nusselt number for some typical Rayleigh number which corresponds to the linear part of the experimental data. The experimental data have been correlated by dimensional analysis. The data have been compared with the empirical correlations and analytical expressions, the correlation used for electroconvection is the correlation used for free-convection. In Figs 11 and 12, the heat transfer correlation of $(Nu_{el})_D$ and Ra_D is plotted for both the experimental results and the predicted values of various correlations for distilled water and RLAP (β-FeOOH) suspension in distilled water. The analytical results are also shown on the same plot. The experimental values in this case predicted a slightly higher Nu_{el} number than the predicted correlations for $Ra > 3.11 \times 10^8$ for distilled water. The corresponding value for RLAP (β-FeOOH) suspension in distilled water is about 2.5×10^8. Curve 1 in Figs 11 and 12 is the predicted correlation obtained by using the equation

$$(Nu_{el})_D = m(Ra_D)^n \tag{13}$$

where the value of m for distilled water and RLAP (β-FeOOH) suspension in distilled water is 0.32, and the corresponding exponent takes the values 0.36 and 0.405, respectively.

Al-Arabi and Khamis [26] have correlated heat transfer data for cylinders of various lengths, diameters and angles of inclination from the vertical. Their results are of the form

$$Nu_L = m(Gr_L Pr)^n$$

where m and n are functions of the cylinder diameter and angle of inclination from the vertical, θ. In the laminar regime, they found

Table 1
The efficiency of convection in RLAP (β-FeOOH) suspension in distilled water under influence of dc field.

Voltage applied to the cylinder (l = 16.0 cm, D = 5.3 cm), U_{dc} (V)	γ (%) of β-FeOOH in distilled water			
	pH = 11.0	pH = 10.0	pH = 9.0	pH = 4.0
0	0	0	0	0
0.01	9.00	4.00	1.00	0
0.02	15.00	7.00	2.00	1.00
0.03	20.00	11.00	4.00	2.00
0.04	24.00	15.00	7.00	4.00
0.05	32.00	18.00	12.00	7.00
0.06	41.00	25.00	14.00	10.00
0.07	46.00	29.00	20.00	13.00
0.08	54.00	36.00	24.00	16.00
0.09	62.00	42.00	26.00	19.00
0.10	67.00	48.00	29.00	23.00
0.20	60.00	45.00	27.00	21.00
0.40	53.00	43.00	25.00	20.00
0.60	48.00	39.00	23.00	19.00
0.80	32.00	36.00	22.00	18.00
1.0	26.00	30.00	20.00	16.00
1.20	12.00	27.00	19.00	15.00
1.40	0	23.00	17.00	14.00
1.60	−14.0	17.00	14.00	13.00
1.80	−30.0	11.00	12.00	11.00
2.0	—	0	9.00	10.00
2.50	—	−9.00	4.00	5.00
3.0	—	−38.00	0	3.00
3.5	—	—	−15.00	0
4.0	—	—	−27.00	−9.00
4.5	—	—	−55.00	−16.00
5.0	—	—	—	−20.00

$$Nu_L = [2.9 - 2.32(\sin\theta)^{0.8}](Gr_L Pr)^{[1/4+(1/12)(\sin\theta)1.2]} \tag{14}$$

where the Grashof number based in cylinder diameter is restricted to the range $1.08 \times 10^4 \leqslant Gr_D \leqslant 6.9 \times 10^5$. For the horizontal cylinder, $\theta = 90^\circ$ and equation (14) becomes

$$(Nu_L)_D = (0.58)\{(Gr_D)^{-1/12}(Ra_D)^{1/4}\} \tag{15}$$

The empirical correlation for free-convection can be used to fit the experimental data for electroconvection if the 1/4th power law in Rayleigh is changed. For distilled water, the exponent of Rayleigh number has been adjusted to 0.375, the corresponding value for RLAP (β-FeOOH) suspension in distilled water is 0.42. This result is represented by curve 2 in Figs 11 and 12. Curve 3 in Figs 11 and 12 resulted from the predicted correlation proposed by Churchill and Chu [27]. For the horizontal cylinder,

$$(Nu)_D = \left\{0.60 + 0.378(Ra_D)^{1/6}\left[1+\left(\frac{0.559}{Pr}\right)^{9/16}\right]^{-8/27}\right\}^2 \tag{16}$$

Equation (16) can be used to fit the experimental data if the 1/6th power law in Rayleigh is changed to 0.20 and 0.225 for distilled water and RLAP (β-FeOOH) suspension in distilled water, respectively. Finally, the experimental results have been compared with the analytical expression available for free-convection [28]. For the horizontal cylinder,

$$(Nu)_D = 0.637(Ra_D)^{1/4}\left(1+\frac{0.861}{Pr}\right)^{-1/4} \tag{17}$$

$$(Nu)_D = 0.678(Ra_D)^{1/4}\left(1+\frac{0.952}{Pr}\right)^{-1/4} \tag{18}$$

The experimental data for electroconvection can be fitted with the analytical expression if the 1/4th power law in Rayleigh is changed to 0.33 and 0.37 for distilled water and RLAP (β-FeOOH) suspension in distilled water, respectively. The result is shown in curves 4 and 5 in Figs 11 and 12, respectively.

Turning now to the overall heat transfer from the heated platinum wire as shown above, the predicted values of the average Nusselt number for Rayleigh numbers 10^8 to 5×10^8 agrees well with the experimental value ($\cong$ 80%). The experimental result predicts a steeper rise in Nusselt number with increasing Rayleigh number than those predicted. The exponent of the Ra_{D} lies between 0.20–0.375 for distilled water. However, the exponent of the Rayleigh number is increased when RLAP (β-FeOOH) is added to distilled water. The result is summarised in Table 3.

The increase in exponent of the Rayleigh number with respect to free-convection indicates that the EOC increases dramatically when an electric field is applied to free-convection motion. EOC is further increased when RLAP (β-FeOOH) is added to distilled water and also, when the surface charge of the particles is increased.

5. Conclusions

This paper reports the experimental results obtained for an EHTC of colloidal RLAP (β-FeOOH) suspension in distilled water in a cylindrical enclosure, under the influence of ac and dc fields. An increase in EHTC is observed in an ac field and the increase is extremely quick for pH values largely different from the IEP. A similar trend is also noticed in a dc field at very weak field strength. An increase in concentration increases the EHTC and similar effect is also noticed when the inclination of the cylinder is changed from the horizontal to vertical position. The experimental data for the hori-

Table 2
The efficiency of convection in distilled water and RLAP (β-FeOOH) suspension in distilled water under influence of ac field

Voltage applied to the cylinder ($l = 16.0$ cm, $D = 5.3$ cm), U_{ac} (V)	γ (%) Distilled water pH = 5.6	γ (%) of β-FeOOH in distilled water					
		pH = 5.6	pH = 7.40	pH = 9.0	pH = 10.0	pH = 10.70	pH = 11.30
0	—	—	—	0	0	0	0
0.10	—	—	—	1.00	1.00	6.00	8.00
0.20	—	—	—	1.00	2.00	12.00	15.00
0.30	—	—	—	2.00	4.00	17.00	24.00
0.40	—	—	—	3.00	6.00	25.00	30.00
0.50	—	—	—	4.00	8.00	30.00	36.00
1.0	—	—	—	4.00	9.00	31.00	38.00
2.0	—	—	—	5.00	10.00	33.00	41.00
3.0	—	—	—	5.00	12.00	35.00	44.00
4.0	—	—	—	6.00	13.00	36.00	50.00
5.0	0	3.0	—	6.00	14.00	38.00	53.00
6.0	3.0	4.5	—	7.00	15.00	40.00	56.00
7.0	5.0	5.0	—	7.50	16.00	42.00	60.00
8.0	6.0	6.0	—	8.00	17.00	44.00	63.00
9.0	6.5	7.0	—	8.5	18.00	46.00	66.00
10.0	7.0	7.5	—	9.0	20.00	50.00	68.00
12.0	8.0	8.5	—	10.0	21.00	54.00	72.00
15.0	9.0	10.0	—	11.5	22.00	60.00	—
18.0	9.5	11.0	—	13.0	24.00	64.00	—
20.0	10.0	12.0	0.50	15.0	30.00	66.00	—
25.0	11.0	13.0	0.70	17.0	38.00	—	—
30.0	12.0	15.0	0.80	19.0	48.00	—	—
40.0	14.0	17.0	0.90	21.00	—	—	—
50.0	17.0	21.0	1.00	25.00	—	—	—
70.0	20.0	25.0	2.0	31.00	—	—	—
80.0	23.0	29.0	3.0	—	—	—	—
90.0	27.0	33.0	5.0	—	—	—	—
100.0	30.0	38.0	7.0	—	—	—	—
106.0	35.0	42.0	8.0	—	—	—	—
110.0	38.0	46.0	9.0	—	—	—	—

Table 3
A comparison of the exponent of the Rayleigh number for various predicted relations used for distilled water and RLAP (β-FeOOH) suspension in distilled water

Curves in Figs 11 and 12	Exponent of Rayleigh number in distilled water	Exponent of Rayleigh number in β-FeOOH in distilled water
1	0.36	0.405
2	0.375	0.420
3	0.20	0.225
4	0.33	0.370
5	0.325	0.368

zontal cylinder have been correlated by dimensional analysis. The data have been compared with the empirical correlation and analytical expression and a good agreement ($\cong$ 80%) is obtained for the Rayleigh number up to 5×10^8. It is observed that the empirical correlation and analytical expression for electroconvection follow laws analogous to free-convection with the exception that the 1/4th power law in Ra_D has been changed and adjusted between 0.20 and 0.42. The higher power law in Rayleigh suggest that the EOC increases dramatically when an electric field is applied to free-convection. The EOC is further increased when the surface charge of the particles is increased. An efficiency of 54% is observed in a dc field corresponding to pH value of 11.0, and an electric potential of 0.08 V. In the case of an ac field, an efficiency of 53% is observed corresponding to an electric potential of 5 V and for a pH value of 11.30. Thus, the electric field required for an ac convection is roughly 63 times larger than the dc convection, and this is due to the relaxation phenomena associated with the ac field. Nevertheless, convection in charge suspensions can be

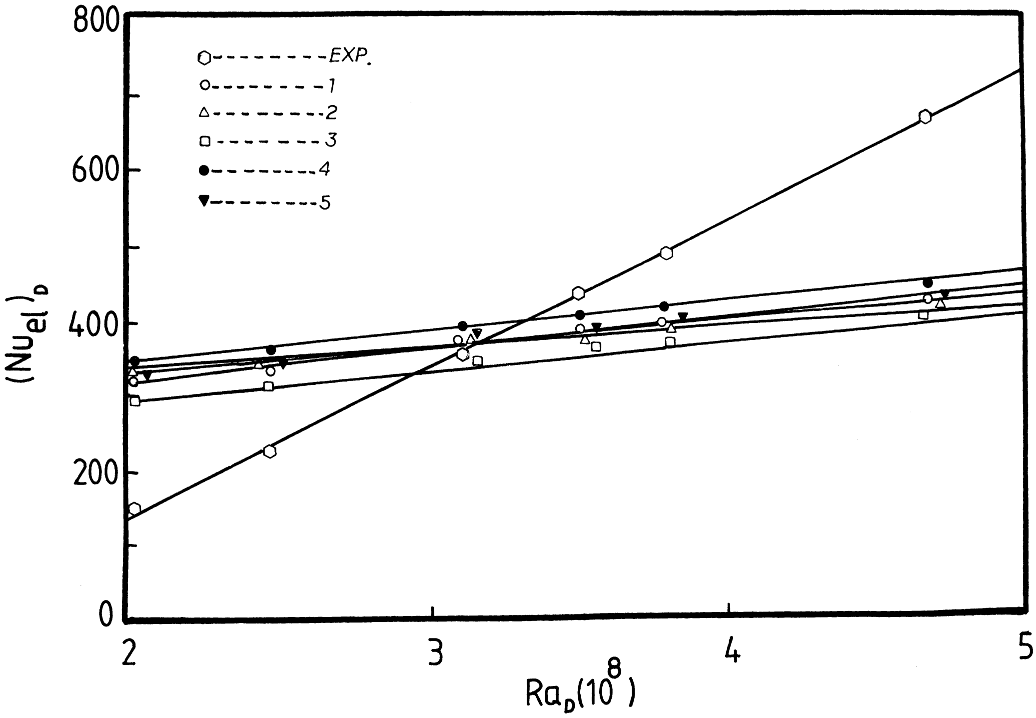


Fig. 11. Correlation of data for EHTC from horizontal cylinder in distilled water. pH value = 5.60. 1: $(Nu_{el})_D = 0.32(Ra)^{0.36}$; 2: $(Nu_{el})_D = (0.58)1/(Gr_D)^{0.05}(Ra_D)^{0.375}$; 3: $(Nu_{el})_D = \{0.60+0.387(Ra_D)^{0.20}[1+(0.559/Pr)^{0.56}]^{-0.30}\}^2$; 4: $(Nu_{el})_D = 0.637(Ra_D)^{0.33}(1+0.861/Pr)^{-0.25}$; 5: $(Nu_{el})_D = 0.678(Ra_D)^{0.325}(1+0.952/Pr)^{-0.25}$.

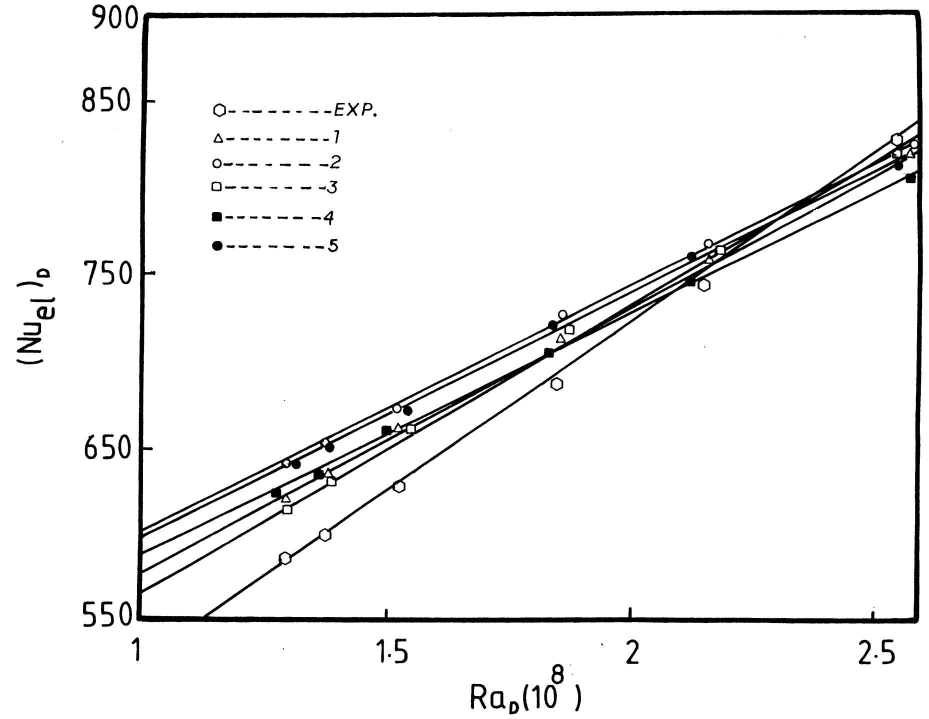


Fig. 12. Correlation of data for EHTC from horizontal cylinder in RLAP (β-FeOOH) suspension in distilled water. pH value = 11.30. 1: $(Nu_{el})_D = 0.32(Ra)^{0.405}$; 2: $(Nu_{el})_D = (0.58)\{1/(Gr_D)^{0.05}(Ra_D)^{0.42}\}$; 3: $(Nu_{el})_D = \{0.60+0.387(Ra_D)^{0.225}[1+(0.559/Pr)^{0.56}]^{-0.30}\}^2$; 4: $(Nu_{el})_D = 0.637(Ra_D)^{0.37}(1+0.861/Pr)^{-0.25}$; 5: $(Nu_{el})_D = 0.678(Ra_D)^{0.368}(1+0.952/Pr)^{-0.25}$.

induced by an extremely low field and this low field eliminates any 'stirring effect' which may result due to electrolysis.

Acknowledgements

The experimental part of the work described in this paper was carried out at the Physics Department, Clarkson University, Potsdam, New York, U.S.A.

The research grant awarded by Abubakar Tafawa Balewa University of Technology, Bauchi, Nigeria, in connection with the preparation of this paper is also gratefully acknowledged.

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