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Study The Combined Effect Of Eof/Pdf On The Performance Of Parallel Flow Microchannel Heat Exchanger At Different Concentrations

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ABSTRACT

In this paper ,a numerical investigation has been made for square microchannel heat exchanger (MCHE) at hydraulic diameter 20 μm, and the diluted water 1:1 potassium chloride (KCl) solution is used as a working fluid at different concentrations ionic concentration $10^{-2}, 10^{-5}, 10^{-8}$ M with a comparison with pure pressure-driven for silicon microchannel. Solving three-dimensional Poisson-Boltzmann equations and Navier-stoke equations with an electric field applied on electrolyte solution using the finite volume scheme. The results showed that ionic concentration plays a significant role in electric double layer thickness and, hence affects on the performance of MCHE, increasing the EDL thickness and increasing the effect of EDL on thermal and hydraulic performance. The ionic concentration is the main parameter that depended on the electric double layer thickness, where the relation between ionic concentration and EDL thickness is reverse as increased the concentration decreasing the EDL thickness. Enhancement ineffectiveness and heat transfer rate with different simple between heat transfer for hot channel and hot channel due to affect the temperature on EDL thickness.

KEYWORDS

Microchannel heat exchanger (MCHE), zeta potential, Electric double layer (EDL), ionic concentration, Poisson Boltzmann equation.

INTRODUCTION

There are basic phenomena of electro-kinetic in microchannel are electro-osmosis, Electrophoresis, electro-migration, and Streaming potential. To transport of fluid in microchannel subject the fluid to electric field is called electro-osmatic flow or applied pressure gradient is called pressure-driven flow or transport of fluid by applied electric field-pressure driven together this called electroomatic/pressure driven flow[1], there are a lot of researches in this field. There are many types of research to study the effect of EDL at pressure-driven or combined PDF/EOF. Mala et al. theoretically and experimentally studied the impact of electric double layer on the flow of water diluted with KCL through two parallel plates; they used different values of ionic concentration, materials of the microchannel (silicon and glass), and height between two plates (10-280 μm) [2]. They discussed the velocity distribution, channel size, and friction factor with EDL effect. Their results refer to that increase in thickness of the electric double layer $1/_k$ with low ionic concentration and high zeta potential, the friction coefficient increased with higher zeta potential. They proved their agreement between theoretical and experimental results and negligible the effect of EDL in the conventional channel. Reza and Mehrdad numerical investigated 3D liquid flow in square microchannel driven by EOF/PDF [3]. They found that the EOF depended on bulk ionic concentration and external electric field. The increase in the external electric field caused a higher velocity of liquid, but the increase in bulk ionic concentration led to a decrease in velocity and electric double layer thickness. Qiao used molecular dynamics simulation to study the effect of rough surface depended on comparable the concave regions with the smooth surface through micro/ nanofluidic [4]. Your results suggest that the distribution of ions for the electric double layer is strongly influenced by surface charge and surface roughness. The distribution of ions is less affectivity at the concave regions than smooth surface Helmholtz-Smolochowski velocity lower in rough micro/Nano channel. Bera and Bhattacharyya numerically studied the combined PDF/EOF flow through single micro/Nanochannels by solving Navier stokes equations with Poisson Boltzmann equation Nernst equation with comparison the results between two methods at thin

EDL and thick EDL [5]. The user liquid is incompressible Newtonian (Nacl with water). They concluded that using a large value of pressure gradient leads to negligible the electrokinetic effect and is similar to Poiseulle flow. THE combined EOF/PDF effect mainly depended on the EDL thickness. Milad et al. numerical and analytical solution for rectangular and circular MCHS to study heat transfer characteristics and Greatz problem with non-uniform heat flux and finite heating length, the driven of flow combined PDF/ EOF at the following assumptions small value of Peclet number and zeta potential with taken the axial conduction and joule heating into account [6]. Their results suggest that analytical solutions agree to a numerical solution, but the analytical solution is active up to Peclet number (10). Moreover, for each of the wall heat flux distribution, the increment in velocity of pressure driven and electric double layer thickness leads to an increase in the average Nusselt number. For all cases, combined EOF/PDF or pure EOF than taken effect of Joule heating rate into account is more complex. Mehdi And Mohammad analytical and numerical solution PDF/EOF driven Newtonian flow through a microchannel with the heterogeneous surface [7]. They found that the Nu decreased with increment pressure force with remand that the electric field's value is fixed, but Nu number increased with increasing electric field and pressure force is fixed. Increment the slip coefficient leads to enhance in the flow of electroosmotic, the reduction in velocity with increasing in Nu number caused in the increased volume fraction of nanoparticles. Lastly, the heterogeneous surface potential can be controlled in the direction and quantity of the velocity field. All the previous research investigated the combined PDF/EOF and pressure-driven EDL effect for a single microchannel. In this work, numerical investigation for performance (thermal and hydrodynamic) of parallel flow microchannel heat exchanger at different ionic concentration with combined pressure-driven / electroosmotic flow.

PROBLEM DESCRIPTION

In this paper, ionic concentration has been studied on performance of parallel flow microchannel heat exchanger as shown in Figure 1, study one unit of microchannel heat exchanger consists of the hot and cold channel shows in Figure. 2, the length of the heat exchanger is1mm and its hydraulic diameter (20μm), the thickness of the wall between the hot channel and cold channel is 3μm, velocity inlet of pressure-driven flow (0.9-6.77) m/s with a constant value of electroosmotic velocity and the temperature of inlet hot and cold are 373 K, 293 K receptivity. The electric potential effect of the surface of the channel (-200 mvolt) and field electric Ez applied on working fluid is $6.64 * 10^6 \frac{V}{m}$. To flow the liquid through microchannel applied pressure gradient and external electric field on liquid, this leads to creating EDL on the liquid-solid interface and affecting the performance of MCHE.

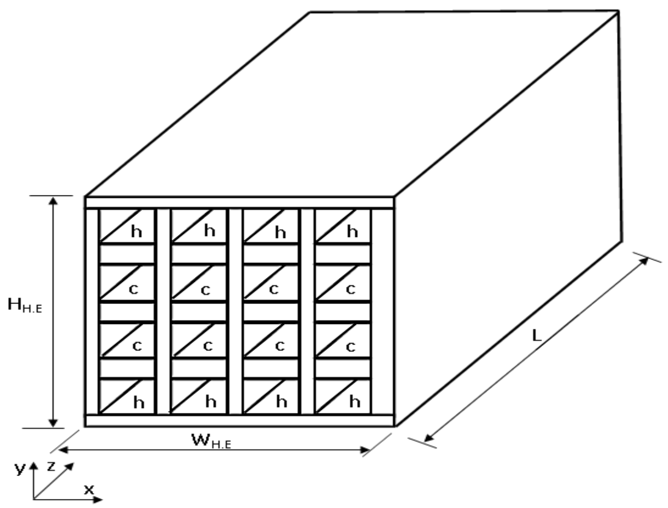

Figure 1. Schematic model of the microchannel heat exchanger.

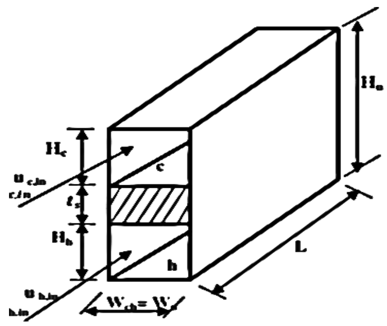

Figure 2. A unit of heat exchanger consists of hot and cold channels at parallel flow [8].

Electric Double Layer (EDL)

The electrical potential surface for a solid wall of the microchannel, the liquid has a few ions, which leads to attraction of the counter-ions in dilute liquid to electrostatic charges of surface to create an electric field of electrostatic charge and ions of liquid is called (EDL). There are two types of ions in terms of motion; for the compact layer (the layer near of surface), the ions are immobile, and in the diffuse double layer (DDL), the electric field less influence to the electric field on the ions (mobile). When the dilute liquid flow during the microchannel, the mobile ions of the electric double layer create an electric current (streaming current) to flow with liquid flow. Gathering of the ions in the direction of flow sets up an electric potential and electric field together known streaming potential. The streaming potential was neglected in the case of electroosmotic flow due to applied electric flied higher than generated streaming potential. The maximum value of the electric double layer (EDL) thickness is 1µm depending on the properties mentioned above. (a) ionic concentration, (b) temperature of the dilute liquid, and (c) zeta potential of the surface. To show characterize of the electric double layer (EDL) effects used the Debye-Huckel parameter k [9]. Figure. 3 shows the formation of EDL on the wall of the channel.

$$k = \frac{\sqrt{2 \mathrm{n_o} \mathrm{z}^2 e^2}}{\sqrt{\varepsilon \varepsilon_{\mathrm{o}} k T f}}$$

$\frac{1}{k}$ referred to as the thickness of the electric double layer (EDL).

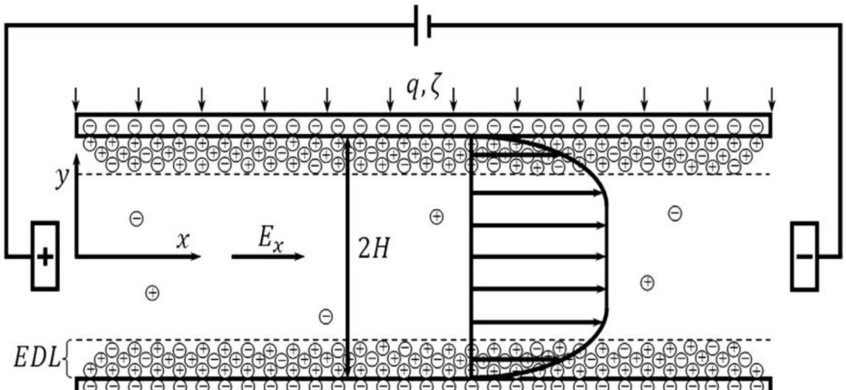

Figure 3. Scheme formed of electric double layer on surface wall [10]

MATHEMATICAL MODEL

Assumptions of flow

- Laminar flow and steady state.
- The working liquid is Newtonian (water diluted with KCL).
- Negligible energy dissipation.

- No heat transfer from/of the ambient.
- Three dimension heat transfer and flow.
- The axial direction is the direction of pressure losses only.

Governing equations

Governing Equations 3D steady-state, incompressible and laminar flow, the following equations are solved to calculate the distributions of velocity, temperature, and EDL distribution for parallel microchannel heat exchanger.

Poisson's equation

According to the theory of electrostatics, the relationship between Ψ and ρe is given by the Poisson's equation [7], which for a rectangular channel

$$\frac{\partial^2\Psi}{\partial x^2}+\frac{\partial^2\Psi}{\partial y^2}+\frac{\partial^2\Psi}{\partial z^2} = -\frac{\rho e}{\varepsilon\varepsilon_o} \quad (1)$$

ε is the dielectric constant of the medium

ε_o is the electric permittivity of a vacuum.

ρe is the net volume charge density, we have

$$ni=n_oi\ exp\left(-\frac{zie\Psi}{kbT}\right) \quad (2)$$

$$\rho e = (n^+ - n^-) = -2n_o zesinh\left(\frac{ze\Psi}{kbT}\right) \quad (3)$$

$n^+ \ and \ n^-$ are the concentration of cations and anions, respectively
Kb Boltzmann's constant $=1.3805 * 10^{-23} Jmol^{-1}K^{-1}$
e electron charge = $1.6021 * 10^{-19} C$
n_oi bulk concentration
Poisson-Boltzmann eq. become [7]

$$\frac{\partial^2\Psi}{\partial x^2}+\frac{\partial^2\Psi}{\partial y^2}+\frac{\partial^2\Psi}{\partial z^2} = \frac{2n_o ze}{\varepsilon\varepsilon_o}\sinh\frac{ze\Psi}{KbT}$$

Continuity equation: [11]

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \quad (4)$$

Momentum equations : [11]

x- direction

$$u\frac{\partial u}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial w}{\partial z}=\frac{\mu}{\rho}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)-\frac{\mu}{\rho}\frac{\partial p}{\partial x} \quad (5)$$

y- direction

$$u\frac{\partial v}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial v}{\partial z}=\frac{\mu}{\rho}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)-\frac{\mu}{\rho}\frac{\partial p}{\partial y} \quad (6)$$

A body force in Z- direction originates due to the presence of the electric field ($Ez\ \rho_e$)

$$u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=\frac{\mu}{\rho}\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)-\frac{1}{\rho}\frac{\partial p}{\partial z}-Ez\rho_e \quad (7)$$

Energy equation:

$$u\frac{\partial T}{\partial u}+v\frac{\partial T}{\partial v}+w\frac{\partial T}{\partial w}=\frac{k}{\rho Cp}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \quad (8)$$

The heat transfer rate of a microchannel heat exchanger between hot and cold[12]:

$$Q = mCp\Delta T \quad (9)$$

The effectiveness (ε)= $\frac{\mathrm{Qact}}{\mathrm{Qmax}} = \frac{\mathrm{Ch(Thi-Tho)}}{\mathrm{Cmin\ (Thi-Tic)}} = \frac{\mathrm{Cc(Tco-Tci)}}{\mathrm{Cmin(Thi-Tci)}}$ (10)

The overall performance of MCHE can be calculated from eq. [12]

$$\eta = \frac{\varepsilon}{\Delta \mathrm{Pt}} \quad (11)$$

ΔPt=ΔPc+ΔPh=(Pin,c-Po,c)+(Pin,h-Po,h) (12)

The inlet velocity determine from Re [12], $v = \frac{Re\ \mu}{\rho\ Dh}$ & velocity of EOF $= \frac{-\varepsilon E z \zeta}{\mu}$ (13)

Boundary conditions

The inlet boundary condition

At inlet of the channel Z = 0, then

U = 0, V=0

W = 1 &T = Tin .

The boundary condition in outlet

At the outlet of the channel Z = Lch and the flow is fully developed, then

$$\frac{\partial u}{\partial z} = 0,$$

$$\frac{\partial v}{\partial Z} = 0$$

$$\frac{\partial w}{\partial z} = 0 \ \& \ \frac{\partial T}{\partial z} = 0$$

Wall

For three cold & hot walls, adiabatic condition is applied:

$$u = 0, v = 0, w = 0, \quad \frac{\partial T}{\partial z} = 0$$

At x=0, $\Psi = \zeta_o$

x=w, $\Psi = \zeta_o$

At y=0, $\Psi = \zeta$

At y=h, $\Psi = \zeta_o$

Water is a working fluid with aqueous KCL solution at the ionic concentration ($10^{-2}, 10^{-5}, 10^{-8}$ M), vacuum permittivity $8.85 * 10^{-12}$(F/m) , dielectric constant ε is 80 and $6.39 * 10^{-10}$ The permittivity of water (C/V*m).

Table 1. The properties of the material for liquid and solid.

material	Density (Kg/m^3)	Cp ($J/Kg.K$)	K ($W/m.K$)	μ ($Kg/m.s$)
Dilute liquid	997	4182	0.605	0.9e-03
Silicon	2329	700	148	-

NUMERICAL SOLUTION

CFD modeling

CFD is a fluid mechanics field to analyze and solve flow problems by using numerical algorithms and computations methods. The computer user to CFD processes must have some advantages such as high speed to carry out the calculations required to determine the parameters that affect the flow of fluid with getting on best results.[13]. The value of the solution converge criteria for continuity, momentum and energy equations and also EDL distribution are used 1×10^{-6}.

Grid independence check

The system of governing equations and the Poisson-Boltzmann equation and boundary conditions are numerically solved using the finite volume method (FVM). A SIMPLE algorithm is used to solve the problem of velocity-pressure coupling and UDF to solve Poisson-Boltzmann equation to study the effect of electric double layer (EDL). ANSYS19 software has been used to do the numerical solution. Table (2) shows independent grid size for hydraulic diameter (20μm) and its effect on the solution results, and the mesh has been used for all calculations to become independent of mesh as shown in this Table**.**

Table 2. Mesh independent

Mesh size	**Outlet temperature (K) of hot channel**	**Outlet temperature (K) of cold channel**
Mesh 2 (size element =3μm)	318.287	347.573
Mesh 3 (size element =1μμm)	318.204	347.302
Mesh 4 (size element = 0.8μm)	318.201	347.30

RESULTS AND DISCUSSIONS

Numerical solution to investigate the effect of ionic concentration on the performance of square parallel microchannel heat exchanger (PMCHE) at three values of ionic concentration ($10^{-2}, 10^{-5}, 10^{-8}$) M and certain hydraulic diameter 20 μm, zeta potential -200 mv, electric field $6.64 * 10^{6}$ m/v and the electrolyte solution using is water dilute Kcl with comparison pure water at pure pressure driven. The length of the microchannel heat exchanger is (1mm), and the thickness of the separation wall is (3μm). The inlet temperatures of hot and cold water used as a boundary condition are Th, in = 373 and Tc, in = 293K. To check the numerical model validity, verification was made by solving the model presented in [3] and compared the results. The model presented in [3] is a square microchannel with a hydraulic diameter of 25 μm, length 1000 μm ΔP/dx =$10^{5}\,\frac{\mathrm{Pa}}{\mathrm{m}}$, the inlet temperature of 289 K. The concentration $10^{-4}, 10^{-5}$ M, zeta potential ζ = 150, 200 m volt, silicon is the metal used in a microchannel.

Figure. 4 shows the comparison between results of the data of [3] for a non-dimensional volumetric flow rate of the microchannel with non-dimensional pressure difference and that for the present numerical model. It can be seen that from this Figure, there is a good agreement between the results of the present model and that for [3] and the error is equal to 3.5 %. **Figure. 5** shows the variation of total pressure drop with velocity inlet of pressure-driven flow at a constant value of electroosmotic flow with different values of ionic concentration of solution through square MCHE parallel flow at certain hydraulic diameter. Can be observed from Figure. the following: the total pressure difference increased with increase in flow velocity of the liquid, and the total pressure drop increased as decreasing the ionic concentration of solution such noted at an ionic concentration equal 10^{-8} M higher pressure drop due to increase of electric double layer thickness with reduced ionic concentration of dilute liquid with high zeta potential -200 mv, and lower pressure losses at high ionic concentration 10^{-2} Moreover, pure water (pure pressure driven flow)` because it less EDL thickness.

Figure. 6 explains the variation of temperature difference (ΔTh) with velocity inlet of pressure-driven flow at a constant value of EOF with different values of ionic concentration of solution through square MCHE parallel flow with two methods of driven flow pure PDF and comparison with combined PDF/EOF. It can be clear from

Figure. that, temperature difference increased with reducing of the flow velocity of the liquid, and the temperature difference increased with higher the ionic concentration of solution such noted at an ionic concentration equal 10^{-8} M higher temperature difference due to increasing the thickness of the electric double layer with the reduced ionic concentration of dilute liquid at high zeta potential -200 mv, increased in EDL thickness means increased in the EDL field. **Figure. 7** indicates the relation between the effectiveness with velocity inlet at a constant value of electroosmotic flow for square PMCHE to study affect the ionic concentration on the performance of the heat exchanger.

Can be observed from Figure. that, the effectiveness decreased with increase in velocity of flow, also notice the effectiveness increased with increasing of ionic concentration of dilute liquid such noted from Figure. 7 at lower ionic concentration lead to high effectiveness due to increase of electric double layer thickness with lowered ionic concentration and hence effect on temperature difference, and observed at the high ionic concentration 10^{-2} and pure water (pure pressure driven flow) is the same effectiveness with different slight due to low EDL thickness. The variation of overall performance with velocity inlet of pressure-driven flow at different values of ionic concentration of solution through square MCHE and comparison between two ways of driven flow mixed PDF/EOF and pure water shows in Figure. 8. Can be concluded from **Figure.8** the following: the performance index reduced as increasing the flow velocity of the liquid, the performance index decreased at a very higher ionic concentration 10^{-2} Mand very lower ionic concentration 10^{-8} M and more decreased at the medium value of ionic concentration due to increase in effectiveness lead to increase in performance more of increase in pressure drop which caused in decreased the performance. Figure. Shows the performance for pure water at pure pressure-driven is greater than it for combined EOF/PDF.

Figure. 9 expresses the variation of heat transfer rate (mCpΔT) with pressure-driven velocity using a constant EOF value with different values of ionic concentration through PMCHE. Can be observed from Figure. that, the heat transfer rate increased with increment the flow velocity of fluid for all cases, and also higher the heat transfer rate at a lower ionic concentration of solution such noted at an ionic concentration equal 10^{-8} M higher heat transfer due to increase of electric double layer thickness with high zeta potential -200 mv this lead to increase exchange heat between the channels (hot and cold). Lower heat transfer at the high ionic concentration 10^{-2} and pure water (pure pressure driven flow. **Figure. 10** explains the relation between pumping power (AvΔP) and inlet velocity with different ionic concentration values to discuss the effect of EDL on P.P. It can be noted from Figure.11 that the pumping power increased with an increase in flow velocity of liquid due to high pressure losses, the P.P increased with lower the ionic concentration of solution such the pumping power increase as lower ionic concentration due to increasing the EDL thickness and lower and effect on pressure drop when the pure water (pure pressure driven has less pressure drop and pumping power.

Figure. 11 shows a comparison between temperature difference in a hot channel and cold channel for microchannel heat exchanger at combined PDF/EOF with two values of ionic concentration 10^{-8}, 10^{-2} M and pure pressure driven. Can be concluded from Figure. 11, there is a different between temperature difference in a hot channel and a cold channel such noted that the temperature difference in hot channel higher than it for a cold channel at combined PED/EOF comparison with pure pressure driven due to the thickness of electric double layer depended on temperature inlet of fluid, as increased the temperature inlet increasing the EDL thickness, therefore, a temperature difference of hot channel higher than temperature difference of cold channel at low ionic concentration and high zeta potential especial at a lower velocity of PDF, from Figure. Noted when high ionic concentration there is slightly different.

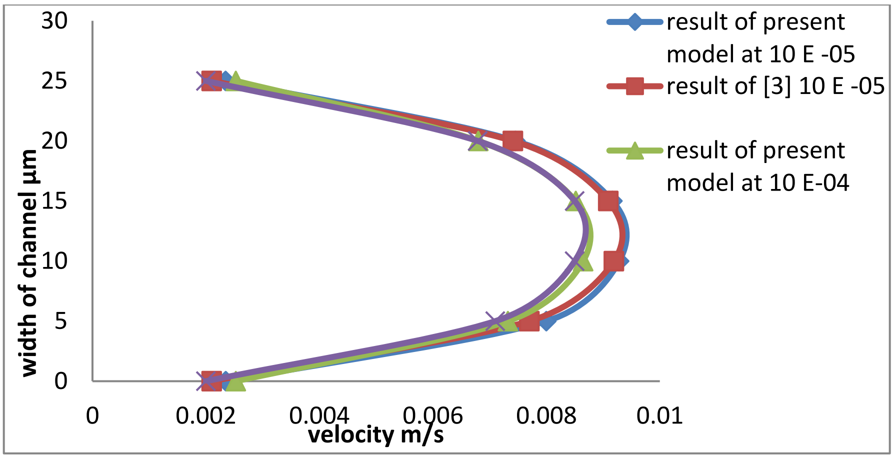

Figure 4. For present model and that for [3]

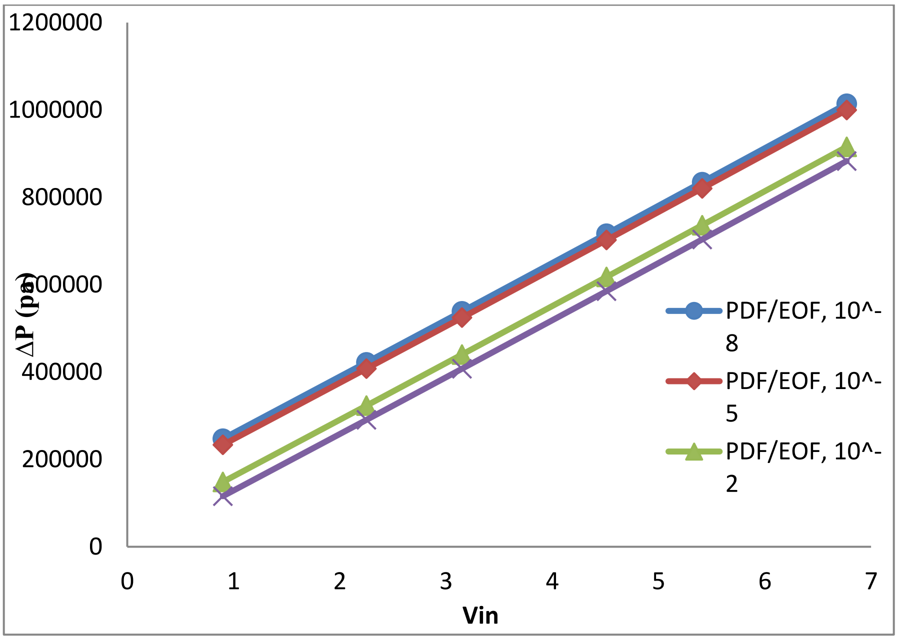

Figure 5. Variation of total pressure drop (pa) with velocity inlet of pressure driven.

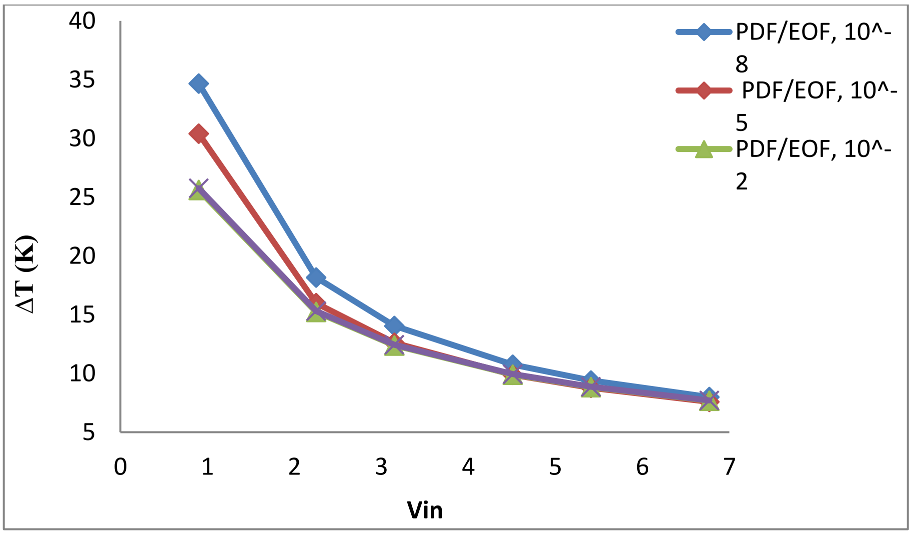

Figure 6. Variation of temperature difference (K) with velocity inlet of pressure driven.

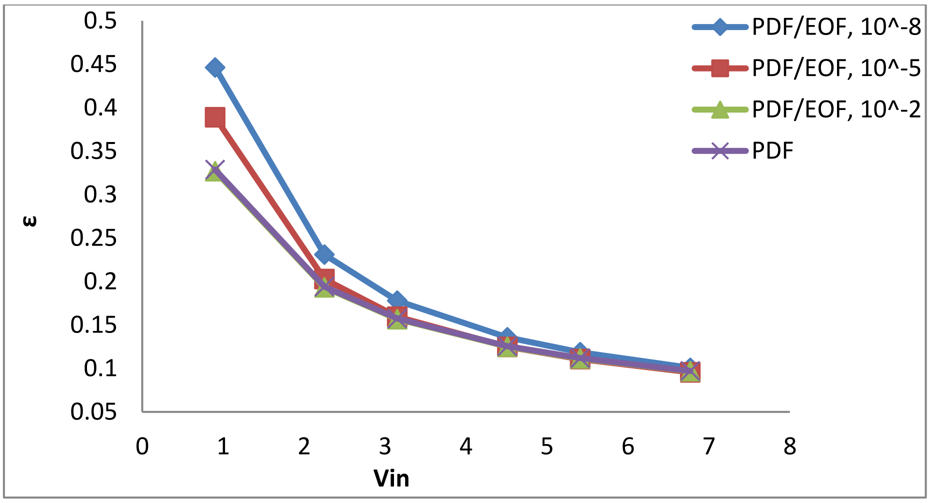

Figure 7. Variation of effectiveness with velocity inlet of pressure driven.

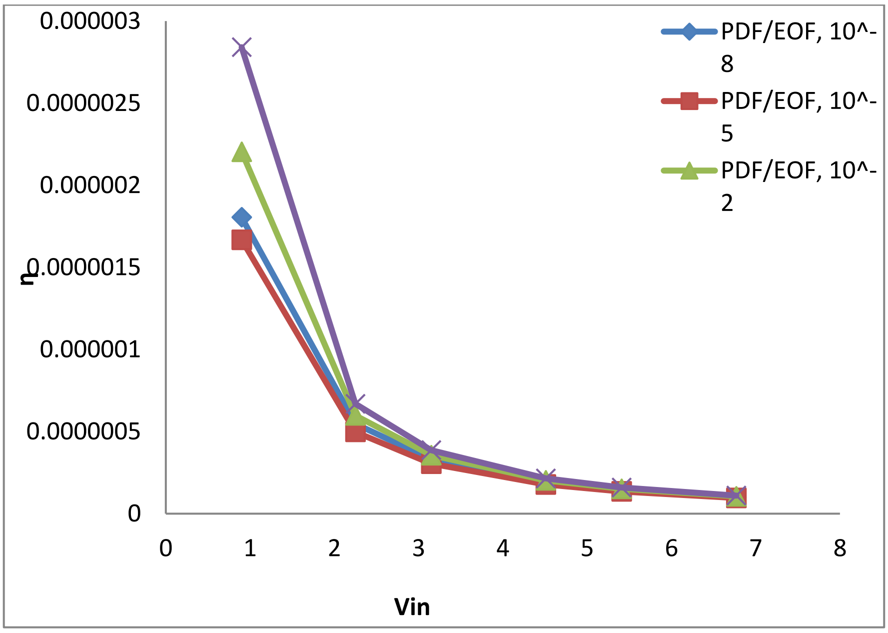

Figure 8. Variation of performance index with velocity inlet of pressure driven.

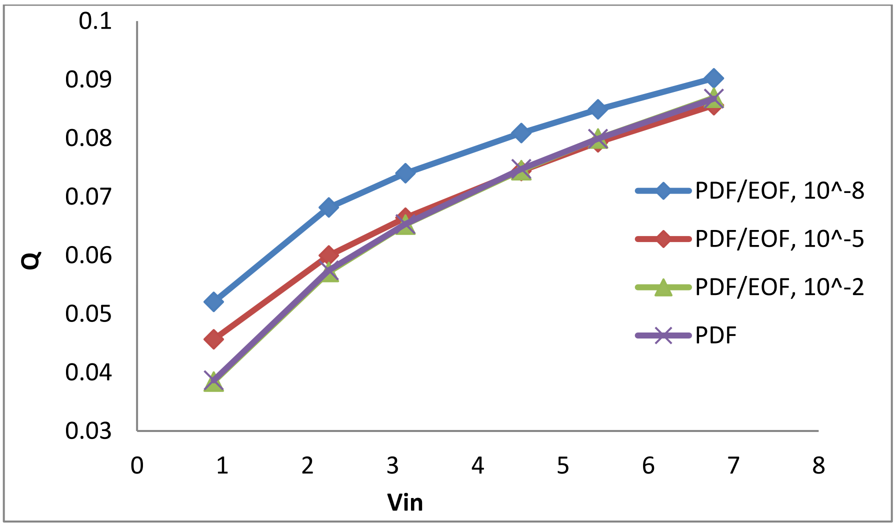

Figure 9. Variation of heat transfer (watt) with velocity inlet of pressure driven .

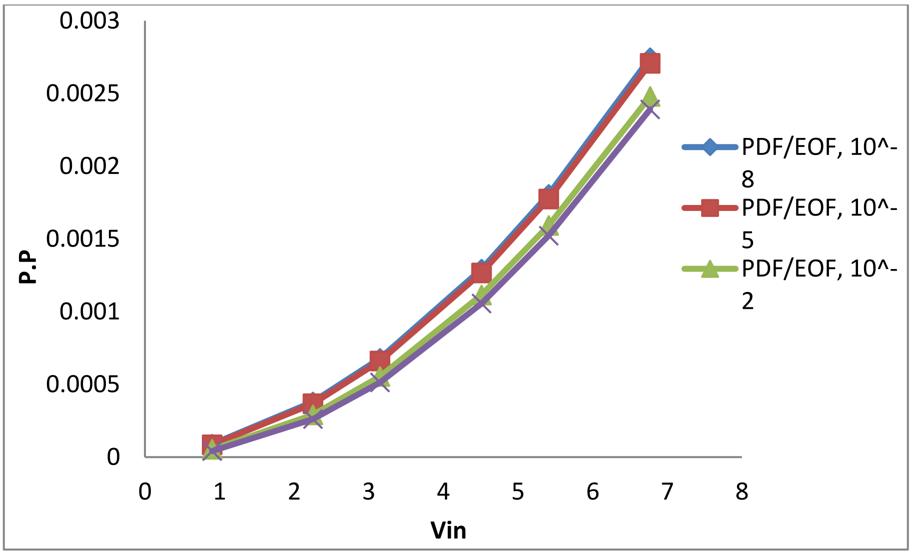

Figure 10. Variation of pumping power (watt) with velocity inlet of pressure driven.

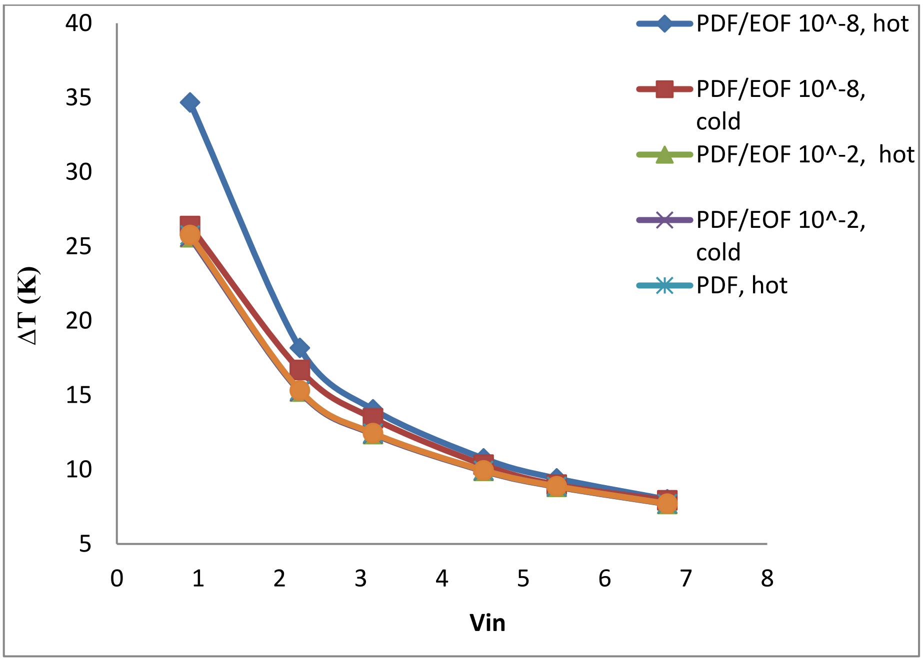

Figure 11. Comparisons between temperature differences for a hot and cold channel with velocity inlet.

CONCLUSIONS

From the obtained results, the following conclude can be made:

- The electric double layer greatly impacts hydraulic performance where it causes an increase in total pressure drop and pumping power.
- Ionic concentration plays a significant role in the effect on electric double layer thickness and hence affects the performance of MCHE, as increased EDL thickness increases the effect of EDL on thermal and hydraulic performance.
- The ionic concentration is the main parameter that depended on the electric double layer thickness, where the relation between ionic concentration and EDL thickness is reverse as increased the concentration decreasing the EDL thickness.
- For combined PDF/EOF, the temperate difference of hot channel higher than cold channel depended on temperature inlet of liquid.

- Enhancement in effectiveness and heat transfer rate with different simple between heat transfer for hot channel and hot channel comparison with pure pressure driven due to effect the temperature on EDL thickness.
- Increased the flow of liquid in the center of channel and decreased inflow at the EDL field when combined EOF/PED.

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