Synthesis and characterization of magnetic $\gamma$-Fe$_2$O$_3$ nanoparticles: Thermal cooling enhancement in a sinusoidal headbox

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ABSTRACT: Nano-size maghemite ($\gamma$-Fe$_2$O$_3$) particles were prepared in one step using ultrasound radiation. The obtained nanoparticles were characterized by SEM, TEM, XRD, FTIR, and VSM. The results revealed that the synthesized nanoparticles were spherical, mono-dispersed and uniform. Furthermore, the crystalline structure of nanoparticles endorsed by X-ray diffraction study. The FTIR spectra have provided information on the structure of the surface of nanoparticles. TEM analysis showed that the average particle size of the $\gamma$-Fe$_2$O$_3$ are about 15 nm. The formed nanoparticles exhibited unique magnetic behavior with magnetic saturation values of ~68 emu/g. By utilizing properties of synthetic $\gamma$-Fe$_2$O$_3$ nanoparticles, a three-dimensional incompressible nanofluid flow in a confined sinusoidal converging jet in turbulent flow regime was numerically investigated. Results were obtained for the flow structure at different Reynolds numbers for steady asymmetric jet development at various values of the duct-to-jet width ratio (aspect ratio), different amplitudes and different volume fractions of nanoparticles. The results showed that by increasing the Reynolds number, aspect ratio, amplitude and volume fraction of $\gamma$-Fe$_2$O$_3$ nanoparticles, the averaged Nusselt number will increase.

KEYWORDS: Maghemite, $\gamma$-Fe$_2$O$_3$; Nanoparticle; Headbox; Heat transfer

INTRODUCTION

Nanoparticles have become the focus of modern materials science because of their potential technological importance, which stems from their unique physical properties [1]. In recent years, metal oxide nanoparticles have attracted substantial interest because of their unique optical, magnetic and electronic properties [2,3]. These properties hold promises for remarkable performance in several important fields of application, including catalytic, magnetic, medicine [4], mechanical and biological applications [5]. Among various transitions metal oxides, maghemite is the most stable iron oxide, low-cost and high resistance to corrosion, which is extensively used as catalysts, gas sensors, anti-corrosive agents, fine ceramics, data storage materials and pigments, light absorption, medicine, adsorbents in waste-water treatment, bio separation. Furthermore, it is considered to be a potential candidate for possible photo electrochemical cells [6-8].

Fluids with suspended nanoparticles are called nanofluid, a term proposed in 1995 by Choi [9] of the Argonne National Laboratory, USA. Nanofluids can be considered to be the next generation of heat transfer fluids because they offer exciting new possibilities to enhance heat transfer performances compared to pure liquids. They are expected to have superior properties compared to conventional heat transfer fluids, as well as fluids containing micro-sized metallic particles [10]. Experimental studies on the heat transfer characteristics of a flow of nanofluids can guarantee high accuracy. However, besides being expensive, it takes a while. Numerical modeling is more effective and workable that can be done within a shorter time and lower cost compared with the experimental method [11].

The headbox is a critical component in the paper making system. The rapidly converging section of a paper machine headbox carries a dilute concentration of pulp fibers to the wire mesh where the fibers are dried to become paper. Rahimi-Esbo et al. [12] numerically studied force convection of turbulent nanofluid flow in a converging duct. Their results show that by increasing the Reynolds number, aspect ratio, and volume fraction the average Nusselt number will increase. Furthermore, they demonstrated in the investigations that increasing the Reynolds number and aspect ratio, the length of the recirculation zones rise. This has a direct impact on the local Nusselt number which, consequently, increases the average Nusselt number.

Esmaeili et al. [13] synthesized the porous superparamagnetic $\text{Fe}_3\text{O}_4$ nanoparticles with an average particlesize of 75 nm through a potentialsolvo-
Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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</thead>
<tbody>
<tr>
<td>AR</td>
<td>Aspect ratio = (h/d)</td>
</tr>
<tr>
<td>c₁,c₂</td>
<td>Constant parameters</td>
</tr>
<tr>
<td>cₚ</td>
<td>Specific heat (kJ/kg.K)</td>
</tr>
<tr>
<td>d</td>
<td>Jet length (m)</td>
</tr>
<tr>
<td>dₑ</td>
<td>Diameter of base fluid molecules (m)</td>
</tr>
<tr>
<td>dₚ</td>
<td>Average diameter of nanoparticles (m)</td>
</tr>
<tr>
<td>h</td>
<td>Height of channel (m)</td>
</tr>
<tr>
<td>j</td>
<td>Colburnfactor (Nu / (Re Pr₁/3))</td>
</tr>
<tr>
<td>K</td>
<td>Thermal conductivity (W/m.K)</td>
</tr>
<tr>
<td>k</td>
<td>Turbulent kinetic energy</td>
</tr>
<tr>
<td>kₜ</td>
<td>Boltzmann number (J/K)</td>
</tr>
<tr>
<td>lₑ</td>
<td>Free average distance of water molecules (m)</td>
</tr>
<tr>
<td>N</td>
<td>Parameter for adapting the results with experimental data</td>
</tr>
<tr>
<td>Nu</td>
<td>Nusselt number</td>
</tr>
<tr>
<td>P</td>
<td>Pressure (Pa)</td>
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<tr>
<td>Pr</td>
<td>Prandtl number</td>
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<tr>
<td>Re</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>T</td>
<td>Temperature (K)</td>
</tr>
<tr>
<td>Tₑ</td>
<td>Bulk temperature of nanofluid (K)</td>
</tr>
<tr>
<td>N</td>
<td>Parameter for adapting the results with experimental data</td>
</tr>
<tr>
<td>Vₜ</td>
<td>Brownian velocity of nanoparticles (m/s)</td>
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<tr>
<td>u</td>
<td>Velocity (m/s)</td>
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Greek symbols

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<tr>
<td>a</td>
<td>Amplitude of the waves (m)</td>
</tr>
<tr>
<td>aₑ</td>
<td>Thermal diffusivity (m²/s)</td>
</tr>
<tr>
<td>δ</td>
<td>Center to center distance of nanoparticles (m)</td>
</tr>
<tr>
<td>ε</td>
<td>Turbulent dissipation rate</td>
</tr>
<tr>
<td>φ</td>
<td>Volume fraction (%)</td>
</tr>
<tr>
<td>λ</td>
<td>Wavelength of the waves (m)</td>
</tr>
<tr>
<td>μ</td>
<td>Viscosity (Pa.s)</td>
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<tr>
<td>ρ</td>
<td>Density (kg/m³)</td>
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<tr>
<td>Γ</td>
<td>Thermal diffusivity</td>
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Subscripts

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<tr>
<td>n</td>
<td>Direction normal on walls</td>
</tr>
<tr>
<td>avg</td>
<td>Average</td>
</tr>
<tr>
<td>f</td>
<td>Base fluid</td>
</tr>
<tr>
<td>in</td>
<td>Inlet</td>
</tr>
<tr>
<td>nf</td>
<td>Nanofluid</td>
</tr>
<tr>
<td>p</td>
<td>Particle</td>
</tr>
<tr>
<td>t</td>
<td>Turbulent</td>
</tr>
<tr>
<td>w</td>
<td>Wall</td>
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Therefore, it is worthwhile to computationally obtain information about the enhancement of heat transfer of γ-Fe₂O₃ nanofluids flowing in a headbox. In this article, γ-Fe₂O₃ nanoparticles were synthesized in one step using ultrasonic radiation and product was investigated in terms of morphology and chemical structure. In the second part, the velocity and temperature distribution, the Nusselt number along both top and bottom walls downstream from the inlet section and the velocity profile at different sections of a paper machine headbox are investigated. Also, the effect of γ-Fe₂O₃ nanoparticles on thermal and flow characteristics and the effect of aspect ratios on flow features and heat transfer properties are investigated.

MATERIALS

The chemical materials used for the fabrication of γ-Fe₂O₃ nanoparticles were Iron(II) chloride tetrahydrate (FeCl₂·4H₂O), Iron(III) chloride (FeCl₃), ammonium hydroxide (NH₄OH), Ethanol (C₂H₅OH) and Hydrochloric acid (HCl) from Merck Co. All these chemicals were used as received without any further purification. Distilled water was used throughout the experiment.

SYNTHESIS OF γ-Fe₂O₃ NANOPARTICLES

Maghemite nanoparticles were prepared in one step as the following: First, 2 ml of HCl (2 mol.L⁻¹) and 20 ml distilled water were added successively to 5.33 g FeCl₂·4H₂O under magnetic stirring. 6.22 g FeCl₃ was dissolved in 38 ml distilled water with stirring and injected to the former solution and stirred at room temperature for minutes to obtain homogeneous solution. After that, 600 ml of NH₄OH (2 mol L⁻¹) solution was added dropwise into the
above solution in an ultrasonic bath at room temperature. A reddish-brown precipitate quickly formed. The precipitate was washed with excess distilled water and ethanol until the pH was adjusted to 3.5 which were repeated at least three times and then dried at 40°C under vacuum oven for 48 hr.

**MODEL DESCRIPTION AND MATHEMATICAL FORMULATION**

For heat transfer of γ-Fe₃O₄ nanofluids flowing in a paper machine headbox, the 3-D incompressible turbulent nanofluid flow is considered. For simplicity, the inlet flow is taken as isothermal, and the velocity profile at the inlet is taken as uniform. The considered geometry and the flow configurations used in this work are shown in Figure 1. The nanoparticles and the base fluid (i.e., water) are assumed to be in thermal equilibrium and no slip condition occurs between them. The other boundary conditions are mentioned in Figure 1.

![Fig. 1.Geometry and boundary condition of the problem](image)

The aspect ratio is taken as follows:

\[ AR = \frac{h}{d} \]  

(1)

The continuity, momentum, and energy equations for the 3-D flow problem are given by the following:

**Continuity**

\[ \frac{\partial}{\partial x_i} ( \rho_{nf} u_i ) = 0 \]  

(2)

**Momentum**

\[ \rho_{nf} \frac{\partial u_i}{\partial x_j} + \frac{\partial}{\partial x_j} \left( \rho_{nf} u_i u_j \right) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] + \frac{\partial}{\partial x_j} \left( \rho_{nf} u_i u_j \right) \]  

(3)

**Energy**

\[ \rho_{nf} \frac{\partial T}{\partial t} + \frac{\partial}{\partial x_j} \left( \rho_{nf} u_i u_j T \right) = \frac{\partial}{\partial x_j} \left( \Gamma \left( \frac{\partial T}{\partial x_j} \right) \right) \]  

(4)

Where \( \Gamma \) and \( \Gamma_t \) are the molecular thermal diffusivity and turbulent thermal diffusivity, respectively, and are given by the following:

\[ \Gamma = \mu_{nf} / Pr_{nf} \quad \Gamma_t = \mu_t / Pr_t \]  

(5)

The Reynolds-averaged approach to turbulence modeling requires that the Reynolds stresses, i.e., \( \rho_{nf} u_i u_j \) be modeled. For this purpose the \( k-\varepsilon \) model is chosen. A common method employs the Boussinesq hypothesis to relate the Reynolds stresses to the mean velocity gradients.

\[ \rho_{nf} u_i u_j = \mu_t \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \]  

(6)

The turbulent viscosity term is needed to be computed, which is defined as follows:

\[ \mu_t = \rho_{nf} \alpha k^2 / \varepsilon \]  

(7)

Following, are transport equations for \( k \) and \( \varepsilon \):

\[ \frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho u_i k) = \frac{\partial}{\partial x_j} \left[ \mu + \frac{\mu_t}{\sigma_k} \right] \frac{\partial k}{\partial x_j} + G_k - \rho \varepsilon + S_k \]  

(8)

and

\[ \frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_i} (\rho u_i \varepsilon) = \frac{\partial}{\partial x_j} \left[ \mu + \frac{\mu_t}{\sigma_\varepsilon} \right] \frac{\partial \varepsilon}{\partial x_j} \]  

(9)

\[ + C_{1\varepsilon} \frac{\varepsilon}{k} \frac{G_k}{C_{2\varepsilon} k} \frac{\varepsilon^2}{k} + S_\varepsilon \]

Where \( G_k \) is the rate of generation of the TKE, and \( \rho \varepsilon \) is its destruction rate, and is written as follows.

\[ G_k = \rho_{nf} u_i u_j \frac{\partial u_j}{\partial x_i} \]  

(10)
$s_k$, $s_\varepsilon$ are source terms for $k$ and $\varepsilon$ and in this research are taken as zero. The boundary values for the turbulent quantities near the wall are specified with the standard wall-treatment method. The values of $c_\mu = 0.009, c_{\varepsilon} = 1.44$, $c_{2s} = 1.92, \sigma_\varepsilon = 1.3$, and are $Pr_t = 0.9$ chosen to be the empirical constants in the turbulent transport equations. The following equations are used to calculate the turbulent intensity ($I$), turbulent kinetic energy ($k$), and turbulent dissipation rate ($\varepsilon$) at the inlet section of the headbox[19, 20].

\begin{equation}
I = 0.16 Re^{-1/8}
\end{equation}

\begin{equation}
k = \left(\frac{3}{2}\right)(I \times u_{in})^2
\end{equation}

\begin{equation}
\varepsilon = c_\mu^{0.75} \times \left(\frac{k^{1.5}}{0.1 h}\right)
\end{equation}

The nondimensional flow and heat transfer parameters are defined by the following:

\begin{equation}
Re = \frac{\rho_{nf} u d}{\mu_{nf}}
\end{equation}

\begin{equation}
Nu = \left(\frac{K_{nf} \partial T}{\partial n}\right) / \left(K_f \left(T_w - T_{in}\right)\right)
\end{equation}

\begin{equation}
Nu_{avg} = \frac{\int Nu(x) dx}{L}
\end{equation}

**THERMOPHYSICAL PROPERTIES OF NANOFIUID**

**Thermal Conductivity**

The thermal conductivity of the nanofluid is calculated from Chon et al. [21], which is expressed in the following form:

\begin{equation}
\frac{k_{nf}}{k_f} = 1 + 64.7 \phi^{0.746} \left(\frac{d_f}{d_p}\right)^{0.369} \times \left(\frac{k_p}{k_f}\right)^{0.7476} Pr_f^{0.9855} Re_f^{1.2321}
\end{equation}

\begin{equation}
Re = \frac{\rho_f k_f T}{3\pi \mu_f \lambda_f}, Pr_f = \frac{\mu_f}{\rho_f \lambda_f}
\end{equation}

According to average diameter of synthetic $\gamma$- Fe$_2$O$_3$ nanoparticles (based on the results of Fig. 4), $d_p$ is taken as 15 nm. $k_f$ is the Boltzmann constant, 1.3807$\times$10$^{-23}$ and $\lambda_f$ is the free average distance of water molecules that according to suggestion of Chon et al. is taken as $d_f$= 0.2 nm, $\lambda_f$ = 0.17 nm. Mintsa et al. [22] approved the accuracy of this model.

**Viscosity**

The viscosity of the nanofluid is approximated as viscosity of the base fluid $\mu_f$ containing dilute suspension of fine spherical particles, as given by Masoumi et al. [23].

\begin{equation}
\frac{\mu_{nf}}{\mu_f} = 1 + \rho_p V_b \frac{d_p^2}{72 N \delta}
\end{equation}

\begin{equation}
N = (c_1\phi + C_2)d_p + (c_3\phi + C_4)
\end{equation}

\begin{equation}
\delta = \frac{\pi}{6 \phi} d_p
\end{equation}

\begin{equation}
V_b = \frac{1}{d_p} \sqrt{\frac{18k_b T}{\pi \rho_f d_p}}
\end{equation}

$N$ is a parameter for adapting the results with experimental data, where $C_1$=-1.133$\times$e$^{-6}$, $C_2$=-2.771$\times$e$^{-6}$, $C_3$=9.0$\times$e$^{-8}$, $C_4$=-3.93$\times$e$^{-7}$.

**Density and specific heat**

The density and specific heat of the nanofluid are calculated by using the Pak and Cho [24] correlations, which are defined as follows.

\begin{equation}
\left(\rho\right)_{nf} = (1-\phi)\rho_f + \phi\rho_p
\end{equation}

\begin{equation}
C_{p,nf} = \frac{(1-\phi)(\rho C_p f) + \phi(\rho C_p p)}{\rho_{nf}}
\end{equation}

\begin{equation}
Pr_f = \mu_{nf} \times \frac{c_{p,nf}}{k_{nf}}
\end{equation}

**NUMERICAL PROCEDURE AND VALIDATION**

A finite volume technique on a collocated grid is implemented for discretizing the governing equations inside the computational domain. The SIMPLE algorithm is used to link the pressure and velocity fields. For the stability of the solution, the diffusion term in the momentum equations is approximated by the second order central difference scheme. Moreover, a deferred correction scheme is adopted for the convective terms. For turbulent equations, the second order upwind scheme is used for discretizing the convection term. For discretizing, the unsteady term implicit Euler and tree times’ level scheme is applied. The Fluent 6.3 software is used for simulation and the nanofluid properties is added to software using user define function(UDF). At the end of any iteration, the residual sum for each of the conserved variables is computed and stored, thus recording the convergence history.
The convergence criterion required that the maximum sum of the error for each of the conserved variables be smaller than $1 \times 10^{-3}$ grid densities of $100 \times 250 \times 100$, $120 \times 270 \times 120$, and $150 \times 300 \times 150$ were selected to perform a grid independency test. Figure 2 shows a less than 1% difference in velocity compared to the chosen grid ($150 \times 300 \times 150$).

For validation purposes, in Figure 3 Colburn factor ($j = \text{Nu} / (\text{Re Pr}^{1/3})$) is compared with numerical result by Pham et al. [25] and experimental data of Zhang et al. [26].

![Figure 2](image2.png)

**Fig. 2.** Midline axial velocity profile for mesh independency investigation at Re=10,000, AR=5, α = 0.02 and φ=0%.

FTIR spectroscopy of $\gamma$-Fe$_2$O$_3$ nanoparticles

The chemical composition and structure of samples were analyzed with Fourier–transform infrared spectrophotometer (FTIR; Burker vector 22 spectrometer, Germany) using KBr pellets, in the range of 400 to 4000 cm$^{-1}$. Figure 5, shows FTIR spectra of the synthesized magnetic nanoparticles.

![Figure 3](image3.png)

**Fig. 3.** Global variations of $j$ heat transfer coefficient versus Reynolds numbers for a wavy channel configuration (Colburn factor ($\text{Nu} / (\text{Re Pr}^{1/3}$))

**RESULTS AND DISCUSSION**

Morphology investigation of $\gamma$-Fe$_2$O$_3$ nanoparticles

The morphology and nanostructure of the $\gamma$-Fe$_2$O$_3$ nanoparticles were investigated using transmission electron microscope (TEM; Zeiss-EM10C- Germany) and scanning electron microscope (SEM; KYKY-EM3200-China). Figure (4a) demonstrate that the magnetic nanoparticles synthesized in this study were spherical and monodispersed. From Figure (4b), it can be obviously seen that the synthesized nanoparticles are in nanometer size with the average size about 15 nm.

![Figure 4](image4.png)

**Fig. 4.** $\gamma$-Fe$_2$O$_3$ nanoparticles a) SEM and b) TEM image

![Figure 5](image5.png)

**Fig. 5.** FTIR spectra of $\gamma$-Fe$_2$O$_3$ nanoparticles
As displayed in Figure 3, the characteristic vibrations of Fe-O in \(\gamma\)-Fe\(_2\)O\(_3\) are clearly observed at 448 and 585 cm\(^{-1}\) [27]. In addition, the peak at 1629 cm\(^{-1}\) is related to the OH bending of water, and the absorption peak at 3405 cm\(^{-1}\) is for the hydroxyl group (–OH) [28]. There is a tiny dip in the spectra at 2368 cm\(^{-1}\) due to the presence of atmospheric CO\(_2\) [29].

X-ray diffraction of \(\gamma\)-Fe\(_2\)O\(_3\) nanoparticles

The crystalline structure of the \(\gamma\)-Fe\(_2\)O\(_3\) nanoparticles was characterized by X-ray diffraction (XRD; INEL, EQuinox 3000, France).

The XRD pattern of \(\gamma\)-Fe\(_2\)O\(_3\) nanoparticles is shown in Figure 6, which agrees well with the reported data (JCPDS card No. 39-1346). Diffraction peaks at 30.2°, 35.5°, 54.1°, 57.7°, and 62.4° are assigned to (220), (311), (422), (511), and (440) crystal planes of \(\gamma\)-Fe\(_2\)O\(_3\). The narrow sharp peaks of the XRD pattern indicate that the \(\gamma\)-Fe\(_2\)O\(_3\) product was well crystallized [30]. The crystalline size of \(\gamma\)-Fe\(_2\)O\(_3\) was calculated by using Scherrer equation:

\[
d = \frac{K\lambda}{\beta \cos \theta}
\]

Where \(d\) is the average crystalline size of the phase under investigation, \(B\) is the Scherrer constant (0.89), \(\lambda\) is the wave length of X-ray beam used (\(\lambda = 0.154\) nm, CuK\(_\alpha\)), \(\beta\) is the full-width half maximum (FWHM) of diffraction and \(\theta\) is the Bragg’s angle. The crystalline size of \(\gamma\)-Fe\(_2\)O\(_3\) was found to be 20.

Magnetic properties of \(\gamma\)-Fe\(_2\)O\(_3\) nanoparticles

The magnetic properties of the \(\gamma\)-Fe\(_2\)O\(_3\) nanoparticles were measured using a vibrating sample magnetometer (VSM; meghnatisedaghiqhakavir, MDK6, Iran). Hematite nanoparticles were dispersed in deionized water by ultrasound (PSA 100-SK1, Korea). Magnetic properties of \(\gamma\)-Fe\(_2\)O\(_3\) nanoparticles were measured at room temperature in applied filed sweeping from +10 to -10 kOe.

As represented in Figure 7 the magnetic hysteresis loops showed S-shaped curves.

Table 1 gives the magnetic parameters such as saturation magnetization (Ms), coercivity (Hc) and remnant magnetization (Mr) that determined by hysteresis loops measurement.

From the Figure 7, it can be seen that the maghemite nanoparticles show ferrimagnetic behavior with magnetic saturation (Ms\(_\gamma\)) value of ~68emu/g.

<table>
<thead>
<tr>
<th>Hc(A/m)</th>
<th>Mr(emu/g)</th>
<th>Ms(emu/g)</th>
<th>sample</th>
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<tbody>
<tr>
<td>67.7</td>
<td>2.4</td>
<td>17.4</td>
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</table>

At high Reynolds number and aspect ratio, an asymmetric flow was observed at flow in a converging sinusoidal channel in a steady solution; so, an unsteady solution was seemed to be necessary.

For the case of AR=10, Re=15,000 an unsteady solution is done and the streamline and temperature contours are simultaneously depicted in Figure 8.
It is observed that after 480 s the streamline remains fixed. According to Figure 8, asymmetric flow occurs for both steady and unsteady cases. It should be noted that the asymmetry in the flow pattern corresponds to a bimodal steady configuration with the jet turning upwards or downwards in a random manner, during any computational run.

Sarma et al. [31] presented this behavior. According to the above proof, the steady solution can be generalized to the unsteady problem. From now on, results are reported on the steady state condition.

In Figure 9 and Figure 10, the steady state streamline patterns at different Reynolds numbers and aspect ratios are depicted. In Figure 9, the effect of Reynolds number on flow structure at AR=10 and $\phi=0\%$ is shown.

It is observed that for a low Reynolds number such as Re=4,000, the jet development is almost symmetric and counter-rotating velocities are seen immediately after the sudden expansion. The jet decay is rapid and the transition from jet-to-duct flow occurs in a short distance. At a higher Reynolds number of Re=10,000, it is observed that the steady state jet flow development is asymmetric. Also, the transition from jet-to-duct flow occurs over a longer distance. For a still higher Reynolds number of 40,000, it is seen that asymmetric flow exhibits a wavy pattern with a larger wavelength and the flow development inside the duct occurs over a larger axial distance. It should be noted that the asymmetry in the flow pattern corresponds to a bimodal steady configuration with the jet turning upwards or downwards in a random manner, during any computational run.
In Figure 10, the influence of aspect ratio on flow structure at Re=15,000 and $\phi=0\%$ is shown. It is observed that for a low aspect ratio such as AR=2, the jet develops almost symmetric and back flow is seen immediately after the sudden expansion. The jet decay is rapid and the transition from jet-to-duct flow occurs in a short distance. At a higher aspect ratio of AR=20, it is observed that the steady state jet flow development is asymmetric. The transition from jet-to-duct flow occurs over a longer distance as well. The main factor for this behavior is velocity difference between main flow at the center of channel and the part of flow that is close to the wall. With increasing aspect ratio velocity of jet flow enhance and velocity difference will be increased and recirculation zone extend.

In Figure 11, the influence of amplitude on flow structure at Re = 15000 is shown. It is observed that for low amplitude there isn’t any recirculation zone in the dip of the wall. At higher amplitude of $\alpha= 0.04$, it is observed that a recirculation zone forms in any wave of the sinusoidal wall. These zones have a great effect on increasing the local Nusselt number.

The effect of amplitude on Nusselt number is depicted in Figure 12. With increasing amplitude recirculation zones are formed in the dip of the wall. In addition chaotic behavior of the fluid flow will be increased and will have more impact between molecules of the fluid and the walls. These impacts cause more energy absorption by the fluid. These cause an average Nusselt number increase on both top and bottom walls.
Figure 13 shows the distribution of the Nusselt number at the top wall for $\text{Re} = 10000$ using different nanoparticles volume fractions. The figure reveals an enhancement in Nusselt number by increasing the volume fraction of nanoparticles. This behavior can be inferred from Equation 16. The effect of nanoparticles on the temperature difference term is negligible.

The effects of volume fraction of nanoparticles on the temperature gradient term and on the thermal conductivity ratio term are more pronounced. Before the point of reattachment as the volume fraction percentage of nanoparticles intensifies the temperature gradient at the top wall increases.

This is related to the addition inertia forces as depicted by Equation 4.

The equations show that any increase in volume fraction increases inertia forces because $\rho_\text{NP}$ will be increased and accordingly increases the temperature gradient. Besides, the nanoparticles increase the thermal conductivity ratio term as it can be seen from Equation 18. Therefore, both the temperature gradient term and thermal conductivity ratio term increase by increasing the volume fraction of nanoparticles. Accordingly, it can be seen that by increasing volume fraction the Nusselt number will be increased, because the heat transfer properties is improved.
Fig. 11. Streamline contours for different amplitude at \(Re = 10000\) and \(AR = 10\). (a) \(\alpha = 0\), (b) \(\alpha = 0.02\), (c) \(\alpha = 0.04\), (d) \(\alpha = 0.05\).

Fig. 12. Effect of amplitude on Nusselt number at \(AR = 10\), \(Re = 10000\).
CONCLUSION

In this paper, we reported the synthesis of maghemite nanoparticles by chemical precipitation route using ultrasonic radiation. Characterization of the obtained product morphology showed that nanoparticles are spherical, monodisperse and have an average core diameter of around 15 nm. The structural characterization of magnetic nanoparticles was further characterized through FTIR spectroscopy and XRD. The XRD pattern indicates that the γ-Fe₂O₃ product was well crystallized. The synthesized nanoparticles exhibited ferrimagnetic characteristics with the maximum saturation magnetization (MS) value of 68 emu/g.

The computational results showed that by increasing the Reynolds number, aspect ratio, volume fraction and amplitude the average Nusselt number will increase. The present computations reveal that when the volume fraction increases gradually from 0.0 to 0.05 the averaged Nusselt numbers will be increase 14 percent. Also 30 percent enhancement in averaged Nusselt number is seen by increasing amplitude from 0.0 to 0.04. It should be noted the intensification of turbulence eddy, suppression of the boundary layer, dispersion of the suspended particles, besides the augmentation of thermal conductivity and the heat capacity of the fluid were suggested to be the possible reasons for heat transfer enhancement.

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