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Investigations on Convective Heat Transfer of Ferrofluids for the Application of Cooling of Photovoltaic Systems

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ABSTRACT

The rheological and thermophysical properties of ferrofluids can be altered in the presence of magnetic field in order to augment the convective heat transfer of ferrofluids. Similar to conventional fluids used for cooling of solar Photovoltaic thermal (PVT) systems, ferrofluids in the presence of magnetic field can be a viable solution for effective cooling of the solar PVT systems. Therefore, with an idea to design a ferrofluid based heat exchanger for PVT systems, the present study aims to investigate the convective heat transfer performance of ferrofluids flowing through mini-channel subjected to anexternal magnetic field and a constant wall temperatureboundary condition. The present study reportsthe variation of convective heat transfer coefficient of ferrofluid flow subjected to different cases (constant and time varying) of magnetic field.For both the cases of constant and time varying magnetic field, the heat transfer coefficient is found to be higher as compared to the case of no magnetic field. However, for time varying magnetic field, the heat transfer coefficient is found to be frequency dependent resulting in either enhancement or decrease in heat transfer as compared to the case of constant magnetic field.

Nomenclature

B	Magnetic flux density (T)
D	Diameter (m)
H	Magnetic field (A/m)
J	Current density (A/m)
M	Magnetization (A/m)
T	Temperature (K)
c	Specific heat (J/kg-K)
F	Force (N)
h	Heat transfer coefficient (W/m^2-K)

Symbols

η	dynamic viscosity (N-s/m^2)
μ	Permeability (m kg s^{-2} A^{-2})
ρ	density (kg/m^3)
χ	Susceptibility (-)

Subscripts

c	characteristic, convection
d	diffusion
f	fluid
ff	ferrofluid
h	hydraulic
m	magnetic
r	remanent , relative
s	surface
v	viscous
w	wall
x	axial/stream wise

Non-dimensional numbers

Nu	Nusselt number $(h.L_c/K_f)$
Re	Reynolds number $(\rho 1.u.D_n/\mu_f)$
x^*	Non-dimensional axial/stream wise length $(x/Re.Pr.D_h)$

Constants

μ_0	Permeability of free space ($1.25663706 \times 10^{-6}$ m kg s^{-2} A^{-2})

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1. Introduction

With the increasing energy demands to improve the living conditions and sustainable growth of the human being, technology has made a shift to develop the methodologies to use renewable sources of energy like solar, wind, tidal and geo-thermal etc. Generating electricity using solar Photovoltaic (PV) systems is one of the state of the art technology in recent times, where maintaining the system temperature within the operating range is essential for maximizing the performance of such PV systems. The operating temperature plays a key role in the PV conversion process. The performanceof a solar PV cell decreases with increasing temperature due to increased internal carrier recombination rates, caused by increased carrier concentrations. It is well known that electrical conversion efficiency decreases with increase of solar cell temperature resulting from absorption of nearly 50% of the total incident energy falling on the surface of the solar cell [Ghadiri et al., 2015]. For example, the efficiency of a typical PV system with c-Si cells decreases by 0.45% for every 1°C increase of the working temperature [Kalogirou and Tripanagnostopoulos, 2006]. Therefore, maintaining the cell temperature of PV systems within the operating range is an important challenge for manyresearchers in the recent time. A typical arrangement of cooling of solar PV cells in order to maintain the temperature within the operating range is shown in Fig. 1.

In the last decade, development of Ferro-hydrodynamics (FHD) is compelling researchers to revisit the thermo-hydrodynamics of the conventional systems with ferrofluid as a working fluid, which is subjected to an external magnetic field. Ferrofluids are magnetic fluids that are synthesized as a stable colloidal suspension of iron oxide (Fe_3O_4) nanoparticles. The nanoparticles are usually coated with a stabilizing surfactant matched with the type of liquid, which prevents the nanoparticle agglomeration, by overcoming the attractive van der Waals forces between the nanoparticles. In the last two decades, ferrofluids have been widely used into a variety of technological (sealing/damping/heat dissipation etc.) and bio-medical applications (drug targeting/hyperthermia etc.). As the rheological and thermophysical properties of ferrofluids change significantly in the presence of magnetic field,it is becoming an area of research for many researchers in the recent time to explore the feasibility of using ferrofluids for heat transfer applications.

Ganguly et al.(2004), have provided an overview of prior reserch related to heat transfer using ferrofluids in the area offree/forced convection, boiling/condensation and multiphase flowsetc., where they have reported the salient features and limitations of each work in details.However, up till nowliterature dealing with the forced convection of ferrofluids in the presence of magnetic field is still limited. Several numerical studies on single-phase convective heat transfer of ferrofluids in the presence of magnetic field are carried out in recent time [Ganguly et al., 2004, Jafari et al., 2007, Xuan et al., 2007, Aminfar et al., 2013]. However, results reported are still insufficient and lacks consistency for designing any ferrofluid based thermal systems.Few experimental studies have reportedan enhancement in heat transfer of ferrofluidic convective flows in the presence of magnetic field while othershave shown either suppression orconditional improvement in heat transfer coefficient [Motozawa et al., 2010, ªeºen et al., 2012, Azizian et al., 2014, Asfer et al., 2016]. Enhancement in the heat transfer was attributed to several factors such asratio of magnetic force to inertia force, increased thermal conductivity and generation of secondary flow due to variation in ferrofluid susceptibility or aggregation formation of nanoparticles near the tube/channel wall. On the other hand, same aggregation of nanoparticles near the zone of highest magnetic force was set responsible for suppression of heat transfer in some of the studies.Other factors like the orientation of applied magnetic field with respect to the ferrofluid flow, source of applied magnetic field (permanent magnet/electromagnet/dipole), particle concentration, and interaction among nanoparticles were also observed to affect the heat transfer of ferrofluids [Li and Xuan, 2009, Lajvardi et al., 2010].

With this background, the presentnumerical study targets to investigate the convective heat transfer of ferrofluids inside a mini-channel under uniform wall temperature condition, subjected to anexternally applied constant/alternating magnetic field. The simulations were carried out using COMSOL□ Multiphysics V4.5 software, while for the validation of numerical results, few experiments were performed only with the constant magnetic field condition.Various results reported in the present study can be interpreted and used further as a guideline for the design of heat exchange thermal systemsfor solar PV systems.

2 Methods

Fig. 2 shows schematic of the 2-D computational domain used in the present study for the convective cooling of ferrofluids in the presence of magnetic field produced by a permanent magnet. Ferrofluids (T= 380 K) with uniform velocity profile was allowed to enter into the channel, while at the exit, flow and thermal conditions were set to be hydrodynamically and thermally fully developed. The bottom wall of the channel was maintained at a constant temperature of T = 300 K, while the top wall was at adiabatic condition. For the generation of magnetic field inside the channel, a permanent magnetof 1 Tesla (B_r= 1.0 Tesla) waslocated below the bottom wall as shown in Fig. 2(a). The computational grid used for the solving of various governing equations was shown in Fig. 2(b).

2.1 Governing equation and Data analysis

The continuity, momentum and energy equations with proper boundary conditions are solved in COMSOL Multiphysics V4.5 platform which is based on FEM (Finite element method) formulation. Flow domain with grids is shown in Fig. 2 (b).

Mass conservation treating flow of ferrofluids as single phaseand incompressible flow:

$$\rho\left(\vec{\nabla}\cdot\vec{V}\right)=0 \tag{1}$$

Momentum equation without viscous dissipation term:

$$\rho\left[\frac{\partial\vec{V}}{\partial t}+\left(\vec{V}\cdot\vec{\nabla}\right)\vec{V}\right]=\vec{\nabla}\cdot\left[-pI+\mu\left(\vec{\nabla}\vec{V}+\vec{\nabla}\vec{V}^{T}\right)\right]+\vec{F} \tag{2}$$

Where $\vec{F}$ represents the magnetic body force term.

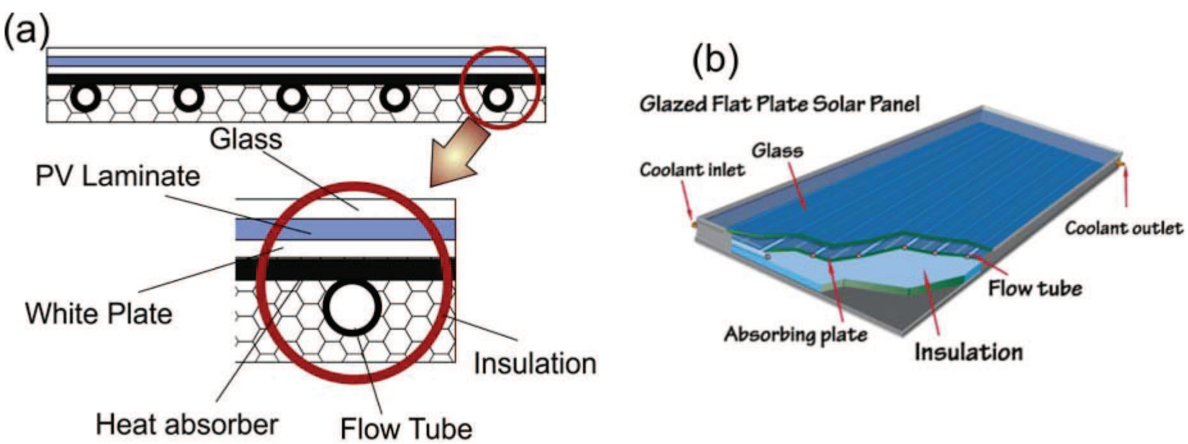

Figure 1 (a) Schematic arrangement of coolant flow in PV cell (b) Picture of PV cell

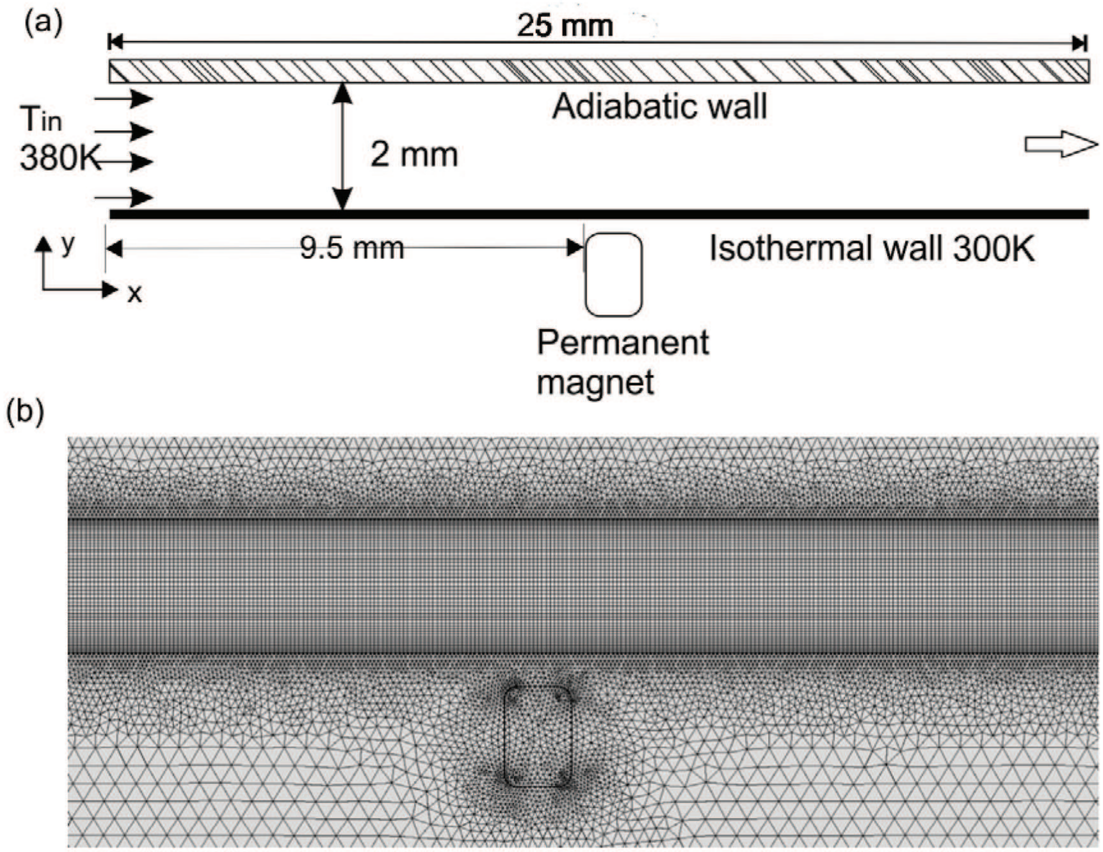

Fig. 2(a) Schematic of computational domain and (b) grid of the computational domain used

The energy equation for ferrofluid is the energy equation for an incompressible fluid and follows the modified Fourier's law as:

$$\rho c_p\left(\frac{\partial T}{\partial t}+\vec{V}.\vec{\nabla}T\right)=k\nabla^2 T \tag{3}$$

The Maxwell-Ampere's law for magnetic field $\vec{H}$ and the current density $\vec{J}$ is expressed as: $\vec{\nabla}\times\vec{H}=\vec{J}\Rightarrow\vec{\nabla}\times\vec{H}=0;$ for non-conducting medium $\vec{J}=0$.

Gauss law for magnetic flux density $\vec{B}$ is expressed as $\vec{\nabla}\cdot\vec{B}=0$, where magnetic flux density and magnetic field for the permanent magnet are given by $\vec{B}=\mu_o\left(\vec{M}+\vec{H}\right)+\vec{B}_r$. Here, the magnetization vector and magnetic field vector are related as $\vec{M}=\chi_m\vec{H}$, where, χ_m is the total magnetic susceptibility of the ferrofluid and it is the function of temperature as $\chi_m=\chi_o\left(T\right)=\frac{\chi_o}{1+\beta\left(T-T_o\right)}$, where, χ_o is the magnetic susceptibility at a reference temperature. Thus, Gauss law and Kelvin body force term can be written as

Gauss law:

$$\vec{\nabla}\cdot\left(\mu_o\left(1+\chi_m\right)\vec{H}+\vec{B}_r\right)=0$$

Kelvin body force: (4)

$$\vec{F}=\left(\vec{M}\cdot\vec{\nabla}\right)\vec{B}$$

$$\vec{F}=0.5\mu_o\chi_m\left(1+\chi_m\right)\vec{\nabla}\left(\vec{H}\cdot\vec{H}\right)+\mu_o\chi_m\vec{H}\left(\vec{H}\cdot\vec{\nabla}\chi_m\right)$$

The steady state local Nusselt number (Nu_x), in case of constant magnetic field, was calculated as $Nu_x=\frac{q''\cdot D_h}{\left(T_w-T_f\right)\cdot k_f}$ while time averaged local Nusselt number (Nu_{ta}) for alternating magnetic field was calculated as $Nu_{ta}=\frac{1}{t}\int_0^t\frac{q''\cdot D_h}{\left(T_w-T_f\right)\cdot k_f}dt$, where T_f was bulk mean temperature of the fluid.

3 Results and Discussion

3.1 Effect of constant magnetic field on heat transfer

This section presents the results obtained for ferrofluidic flow through the mini-channel subjected to a constant magnetic field (B_r =1T). Fig. 3(a) shows the comparative variation of the velocity and temperature field inside the mini-channelwithout and with magnetic field respectively. From the velocity field (Fig. 3(a)), it wasobserved that the streamwise velocity 'u' increases in the upstream region in the vicinity of the magnet location, whereas it decreases in the downstream region to the magnet location.This was because of orientation of the magnetic force with respect to the inertia force in the vicinity of the magnet location. At the upstream region, the magnetic force on ferrofluid was acting in the same direction as that of inertia force resulting in increase in 'u' streamwise velocity component locally as shown in Fig. 3(a). However, at the downstream region of the magnet, the magnetic force opposed the inertia force acting on ferrofluid resulting in a local decrease in 'u' velocity component in stream wise direction.

For the present configuration, the *x*-component of magnetic force (F_x) was changing its sign from positive to negative along the *x*-direction while, the *y*-component of magnetic force (F_y) was always acting downward, i.e., in –ve *y* direction.As a consequence, ferrofluid experienced a strong

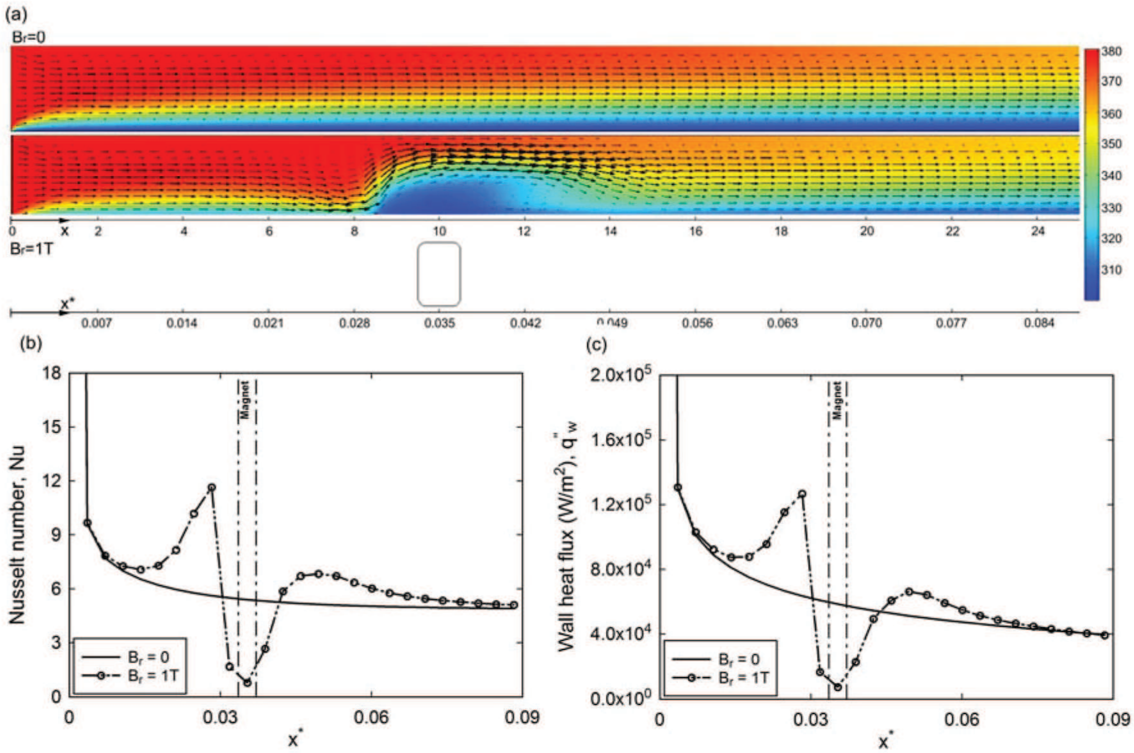

Figure 3 (a) Variation of velocity and temperature field inside the mini-channel without and withconstant magnetic field, (b) stream wise variation of Nusselt numberand (c) stream wise variation of wall heat flux.

magnetic force in the vicinity of magnet, resulting in a zone of stagnant layer of ferrofluidnear the bottom wall as clearly visible in Fig 3(a). The stagnant zone of ferrofluid was observed to act as an obstacle to the flow and giving rise to the generation of secondary flow, which subsequently formed a recirculating zone in the downstream region of the stagnant ferrofluid as shown in Fig. 3(a). The corresponding temperature field of ferrofluid in the presence of magnetic field superimposed with the velocity field wasalso shown in Fig. 3(a). Fig. 3(b) and 3(c) show the comparison of the stream wise variation of Nusselt number and wall heat flux for the cases of with and without magnetic field. A region of high temperature gradient was observed at the upstream and downstream region of the stagnant ferrofluid layer as shown in Fig. 3(a). Nusselt number and wall heat flux were observed to be higher at the upstream and downstream region of magnet location, whereas a drop in both the quantities were observed at the magnet location as shown in Fig. 3(b) and 3(c) respectively. The recirculation zone as discussed above resulted in movement of hot fluid in the cross stream wise direction resulting in higher heat transfer at the downstream region, whereas the acceleration of ferrofluid was found to be responsible for higher heat transfer at the upstream region. The stagnant ferrofluid layer suppresses heat transfer from hot ferrofluid to cold bottom wall resulting in a drop in Nusselt number at the magnet location as shown in Fig. 3(b).

3.2 Effect of time varying magnetic field on heat transfer

It is evident from the above discussion that no heat transfer enhancement occurs between the hot ferrofluid and the bottom wall at the magnet location in the presence of a constant magnetic field. In order to enhance the heat transfer at the magnet location in the presence of a constant magnetic field, the stagnant layer of ferrofluid must be disturbed so that momentum or energy transfertakes place between the hot ferrofluid and the cold bottom wall. Therefore, time varying magnetic fields at different frequencies were imposed and studied in the next section to observe the effect on convective heat transfer compared to that of constant magnetic field.

Fig. 4 presents the velocity and temperature field inside a channel under the influence of time varying magnetic field. The variation of applied magnetic field with time was primarily a square wave (ON/OFF) with an amplitude of 1.0 Tesla and frequencies ranging from 0.5 to 10 Hz. A temporal variation in velocity and temperature field was observed within the magnetically active region for the case of time varying magnetic field as compared to the constant magnetic field. The location, shape and size of the stagnant ferrofluid layernear the magnet location was observed to change at different time stamps within one-time period of magnetic field actuation (Fig. 4). During the OFF mode of magnetic actuation for frequency$f$ = 0.5 Hz, ferrofluid layer was observed to decrease in size and then slowly advected to the downstream region as shown in Fig. 4(a). This is because of negligible dominance of magnetic force over the inertia force during the OFF mode resulting in advection of ferrofluid from stagnant ferrofluid layer to the downstream region. Similar results were observed for the actuation frequencies up to f = 2.5 Hz as shown in Fig 4(b) and 4(c) respectively. However, the rate of advection of ferrofluid from stagnant layer to the downstream was observed to decrease at higher frequencies f> 2.5 Hz as shown in Fig. 4(d).

This happened because the convective time scale $(t_c=L_c/U_{avg})$ was found tobe comparable to magnetic field perturbation time scale $(t_m = 1 / f)$ up to 2 Hz. As the frequency of magnetic field pulsation increased, the L_c/U_{avg} was always found togreater than 1/f, i.e., advection is sluggish. During OFF mode at 0.5 Hz and 1 Hz, velocity profilewasgradually developed as fully developed parabolic profile, but as the magnetic field pulsating frequency increased beyond 1 Hz, flow never became set up as fully developed situation. This is mainly due to the fact that the viscous diffusional time scale $(t_v = L_c^2 / V)$ was quite higher than magnetic field perturbation time scale $(= 1/f)$, i.e., diffusion of momentum is sluggish as compared to the externally imposed disturbances in terms of magnetic field fluctuations.

It can also be noticed that temperature field fluctuation and recirculation strength increases for the magnetic field frequency varying from 0.5 - 2.5 Hz, while for 10 Hz, temperature and flow field becomes insensitive to the magnetic field pulsations. It is mostly behaving like constant magnetic field case. This is mainly due to the fact that at 10 Hz, all the time scales e.g., hydrodynamic diffusion time scale $(= L_c^2 / V)$, thermal diffusion time scale $(t_t = L_c^2 / \alpha)$ and convection time scale (L_c / U_{avg}) were significantly higher than magnetic field perturbation time scale. Therefore, any rapid disturbances created externally could not be able to either advect or diffuse into flow/thermal field.

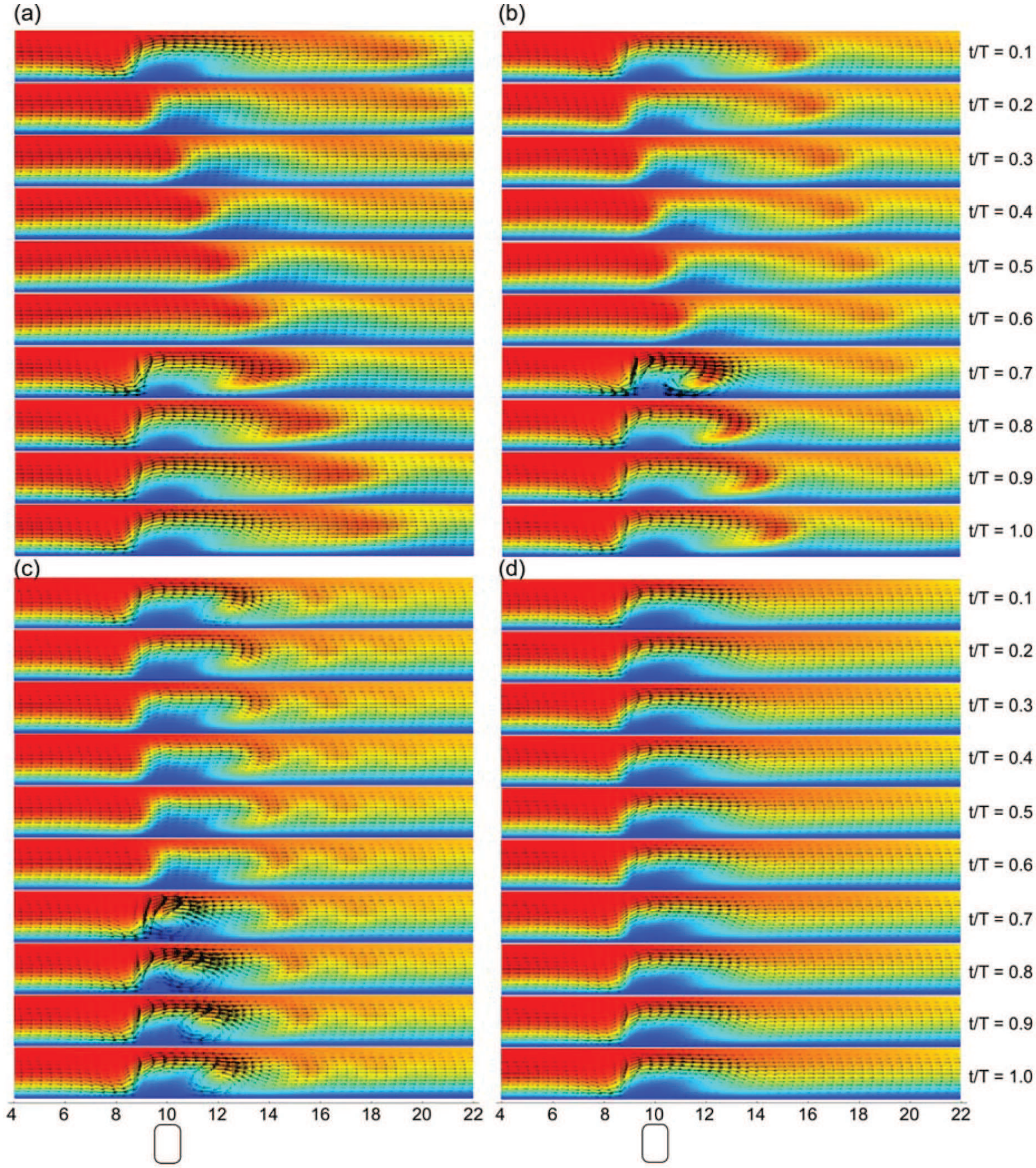

Figure **4.** Velocity and temperature field inside the mini-channel subjected to the time varying magnetic field: (a) 0.5 Hz (b) 1 Hz (c) 2.5 Hz (d) 10 Hz respectively.

Fig. 5(a) shows the comparison of stream wise variation of time averaged local Nusselt number for the cases of without magnetic field and with magnetic field (constant as well as time varying). The inset image shows the stream wise and time averaged Nusselt number for all cases as mentioned above.Significant improvement in *Nu* was observed in case of convective flow with externally applied magnetic field whetherthe magnetic field is constant or time varying.Moreover, when comparing the two cases of constant and time varying magnetic field, it was seen that enhancement in Nusselt number is dependent on frequency of applied magnetic field. Overall value of Nusselt number during pulsating magnetic field up to 2.5 Hz was found to beapproximately similar as constant magnetic field case for $Re = 25$. However, as the frequency increased, i.e., for 4 Hz and 10 Hz, change in Nusselt number was found to be negative as compared to constant magnetic field case, though *Nu*was still found to be higher than the value of no magnetic field case. With this contextual discussion, it is clear that application of external magnetic field during the convective flow of ferrofluids certainly improves the heat transfer in the interplay of inertia force, viscous force and magnetic body force. Of course, with time varying magnetic field, due to unsteadiness and periodicity, the effect of different forces has to be perceived from involved time scales viewpoint. Also, no monotonic increase or decrease in *Nu*was observed with frequency.

In order to have confidencein the present results, qualitativecomparison has been shown for the variation of Nusselt number with one of our previous experimental work [Asfer et al., 2016]. The experimental study of convective flow of ferrofluidswas carried out inside a stainless steel (SS) tube of 2 mm/ 2.6 mm (ID/OD), subjected to a constant non-uniform magnetic field produced by pairs of permanent magnets of remanent magnetic flux intensity of 1 Tesla.The details of experimental set-up and measurement methodologies can be found in the work by Asfer et al., 2016. Fig. 5(b) shows the stream wise variation of the Nusselt number *Nu*, for the case of constant magnetic field.A similar trend was observed in Fig. 5(b) as compared to the present numerical results as shown in Fig. 5(a). Various factors such as: (a) ratio of magnetic force to inertia force, (b) interaction of ferrofluid flow with the aggregate of nanoparticles at the wall of the tube adjacent to each magnet, and (c) enhancement in local thermal conductivity of ferrofluid were arguedfor the overall increase or decrease in convective heat transfer characteristics of ferrofluid in the presence of magnetic field. Conclusions derived from the present numerical resultsare in qualitative agreement with that of our previous experimental results as discussed above. It is noteworthy to mark the differences exist between the present simulation and previous experiments such as: (a) in simulations, ferrofluids have been considered as magnetically activewithout any nanoparticles suspension but actually, ferrofluids are colloidal suspension of nanoparticles in base fluids (b) in

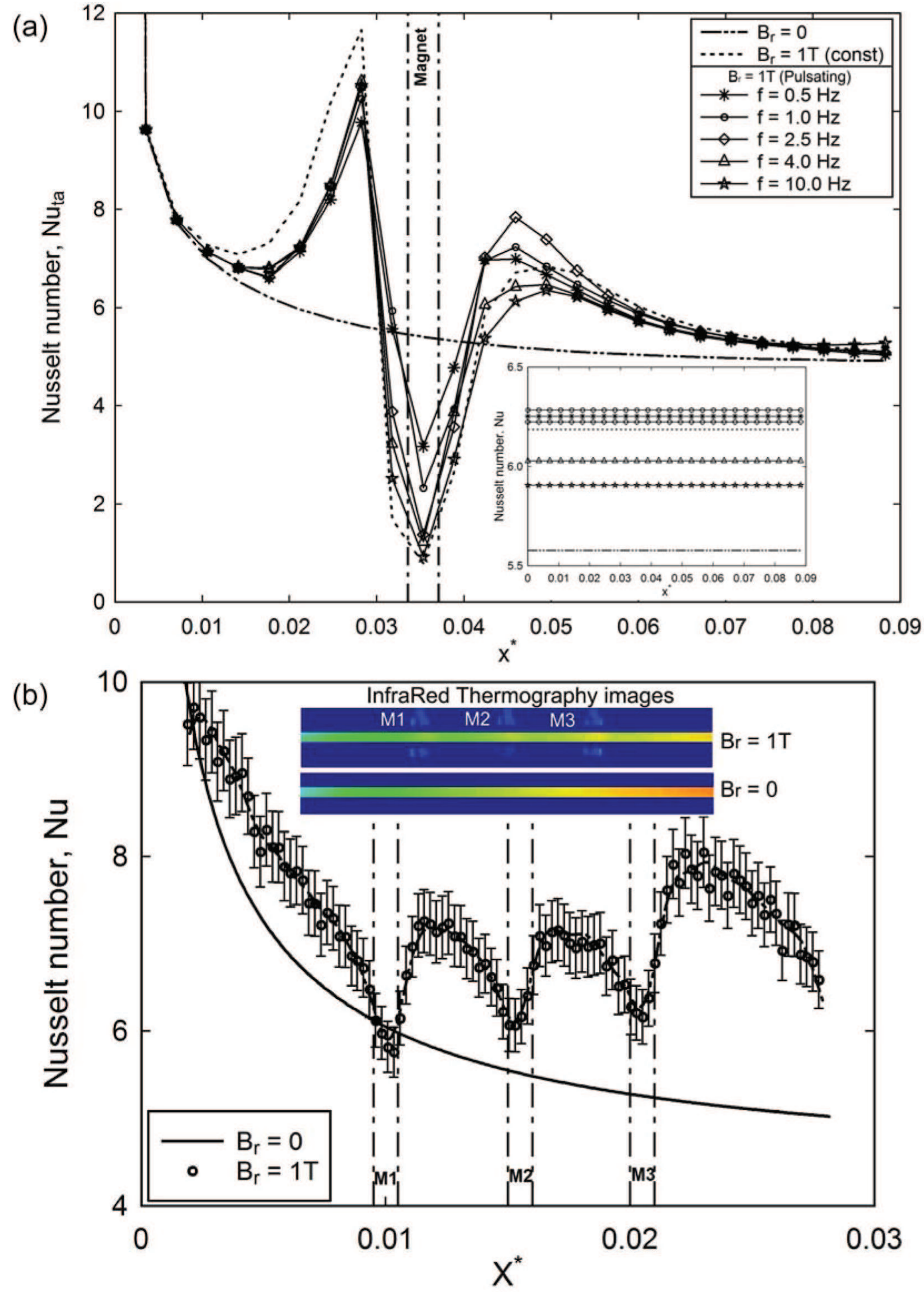

Figure **5.**Stream wise variation of (a) local time averaged Nusselt number, Nu_{ta} and inset image showing thestream wise and time averaged Nusselt number for different magnetic field strengths (b) local Nusselt number, *Nu*, obtained from experiments for constant magnetic field and inset image showing the InfraRed thermographic image (IRT) of wall temperature.

reality, clustering of nanoparticles occur in the bulk fluid under the influence of magnetic field which was absent in simulationsand (c) nanoparticles deposit near the magnet resulting in the formation of aggregate and subsequently reduce the concentration of nanoparticles in the bulk fluid.In spite of these differences, the qualitative agreement between simulations and experimental results are quite encouraging for further numerical explorations. Thus, it can be comprehended that integrating the heat exchanger based on ferrofluids to PV systems might be useful to extract the heat which increases the temperature of the cell.

4 Conclusions

In the present work, the laminar convective heat transfer characteristics of ferrofluid flowing through a mini-channel in the presence of a constant and time varying magnetic field are investigated from the perspective to develop a ferrofluid based heat exchanger for PVT systems. The major conclusions of the present study are as follows:

- The Nusselt number for ferrofluid flow increases for both the cases of applied magnetic field i.e. constant and time varying as compared to the case of no magnetic field. For time varying magnetic field, Nusselt number was found to be more frequency dependent resulting in either enhancement or decrease in heat transfer as compared to the case of constant magnetic field.
- Overall value of Nusselt number for time varying magnetic field (up to 2.5 Hzand Re = 25) is found to be nearly similar with that of constant magnetic field case. However, as the frequency increased, i.e., for 4 Hz and 10 Hz, change in Nusselt number was found to negative as compared to constant magnetic field case, though Nu was found to still higher than the value of no magnetic field case.
- Enhancement or decrease in heat transfer in the presence of time varying magnetic field isattributed to several factors such as: (a) ratio of magnetic force to inertia force, (b) shape, size and location of stagnant layer of ferrofluid formed at the magnet location and (c) the role of various time scales involvedduring the transportation of ferrofluid in the presence of magnetic fieldsuch as convection and magnetic field perturbation time scales etc.

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