Semnan University

Journal of Modeling in Engineering

Journal homepage: https://modelling.semnan.ac.ir/

ISSN: 2783-2538



Improving the Pressure Drop and Heat Transfer of Forced Convection of Liquid Metal by Applying Direct and Alternating Magnetic Fields

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Received: 2024-01-11 Revised: 2025-06-29 Accepted: 2025-07-07

Abstract

Increasing the heat transfer rate is essential in many industries to improve equipment efficiency, prevent component damage and reduce costs. One solution is the use of active and passive heat sinks. In this research, an active heat sink with the liquid metal Galinstan as the working fluid is considered. The Navier–Stokes equations are discretized using the second-order upwind finite volume method. A magnetic field applied in the Y direction (perpendicular to the flow axis) produces a Lorentz force opposing the flow, which creates an M-shaped velocity distribution: the velocity increases near the walls and decreases along the microchannel centerline. In contrast, an alternating magnetic field applied in the X direction flattens the velocity profile. Both direct and alternating fields improve the Nusselt number: an alternating field in the Y direction improves it by 38%, and a field in the X direction by 11.62%. The resulting increase in the velocity gradient also increases the friction coefficient. By varying the phase difference between the magnetic and electric fields from zero to 90 degrees, it is shown that the pressure drop and the friction coefficient caused by the magnetic field decrease.

Keywords:

Forced convection heat transfer, Liquid metal, Direct and alternating magnetic field, Heat sink.

1. Introduction

Rapid development of the computer industry has made cooling of electronic components challenging, and microchannel heat sinks can remove a large heat flux from a small surface [1,2]. Compared with conventional coolants, liquid metals have a much higher thermal conductivity and are therefore more effective at removing heat from a hot source [3]; Galinstan, for example, can reduce the overall thermal resistance of a heat sink by about 40% relative to water [4].

Because of their high electrical conductivity, liquid metals respond strongly to magnetic fields, whose effect on heat transfer and pressure drop depends on the field direction. Hajmohammadi et al. [5] reported that a uniform external field can reduce the thermal resistance of microchannel heat sinks by up to 21%, and Abadeh et al. [6] found that an alternating field increased the Nusselt number of a ferrofluid by 11.85% and 14.8% at 10 and 100 Hz. Nouri et al. [7] reported that a field perpendicular to a sinusoidal channel increases the Nusselt number. Wang and Lei [8] showed that increasing the Hartmann number enhanced the convective heat transfer of liquid metal in a rectangular microchannel by 32%, but at the price of a strong rise in the pressure drop and friction coefficient.

Since this pressure-drop penalty limits the practical use of magnetic fields, the present study aims to improve heat transfer while reducing the pressure drop. Its novelties are: (i) Galinstan is used as the working fluid of an active heat sink; (ii) the effects of direct and alternating magnetic fields are compared; (iii) fields perpendicular to the flow axis (X and Y directions) are studied; and (iv) the phase difference between the magnetic and electric fields is examined as a means of reducing the friction coefficient and pressure drop.

2. Methodology

2.1. Geometry and assumptions

The heat sink consists of 20 identical rectangular channels with the same heat and mass transfer behavior, so a single channel is analyzed, as in Sarowar [9] (Figure 1). The channel height is H = 5 mm, the channel width W_c = 1 mm, the

wall thickness W_w = 1 mm, the base thickness t_b = 2 mm, and the overall size is $W \times L$ = 4 cm × 4 cm. The working fluid is Galinstan (Ga68%In20%Sn12%) with the following properties at 290 K [8]: density 6360 kg/m³, specific heat 365.8 J/(kg·K), dynamic viscosity 0.0022 Pa·s, thermal conductivity 16.5 W/(m·K) and electrical conductivity 3.31×10^6 S/m. The flow is incompressible and single-phase with no slip at the walls; the body forces are the Lorentz force and gravity; viscous dissipation, radiation, Joule heating and the ferromagnetic term are neglected. Direct-field cases are solved as steady and alternating-field cases as transient.

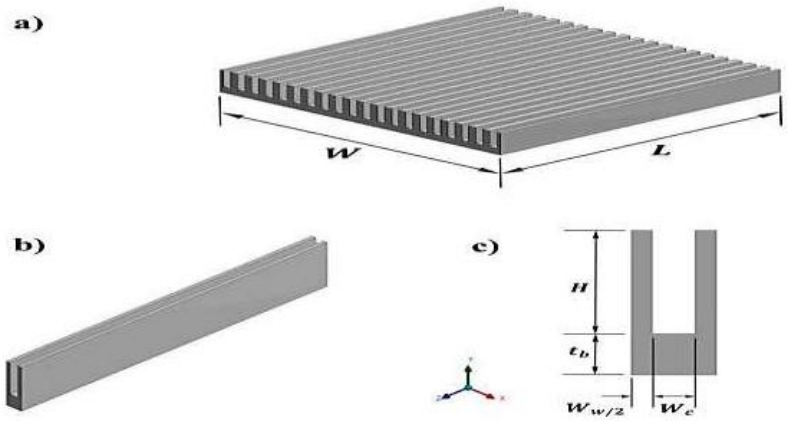


Figure 1. (a) Complete three-dimensional geometry of the heat sink, (b) a single microchannel, (c) cross-section of the channel with its dimensions [9].

2.2. Governing equations

The flow is governed by the continuity equation ($\nabla \cdot \mathbf{V} = 0$), the momentum equation (1) and the energy equation (2):

$$\rho\left[\frac{\partial \mathbf{V}}{\partial t} + (\mathbf{V}\cdot\nabla)\mathbf{V}\right] = -\nabla p + \mu\nabla^2\mathbf{V} + \mathbf{F}_L + \rho\mathbf{g} \tag{1}$$

$$\rho c_p\left[\frac{\partial T}{\partial t} + (\mathbf{V}\cdot\nabla)T\right] = k\nabla^2 T \tag{2}$$

where $\mathbf{V}$ is the velocity, p the pressure, ρ the density, μ the viscosity, c_p the specific heat, k the thermal conductivity, $\mathbf{g}$ the gravity and $\mathbf{F}_L$ the Lorentz force. For a direct field the Lorentz force opposes the flow with a magnitude of $\sigma B_0^2 V$. For an alternating field, the electric and magnetic fields are

$$\mathbf{E} = E_0\sin(\omega t + \varphi), \quad \mathbf{B} = B_0\sin(\omega t) \tag{3}$$

where ω is the angular frequency and φ is the phase difference of the electric field relative to the magnetic field. The current density is

$$\mathbf{J} = \sigma(\mathbf{E} + \mathbf{V}\times\mathbf{B}) \tag{4}$$

and the Lorentz force averaged over one period is

$$\bar{\mathbf{F}}_L = \frac{1}{2\pi}\int_0^{2\pi}(\mathbf{J}\times\mathbf{B})\, d(\omega t) \tag{5}$$

The magnetic effect is expressed by the Hartmann number

$$Ha = B_0 L\sqrt{\sigma/\mu} \tag{6}$$

where B_0 is the field strength and L the characteristic length. The Reynolds number is $Re = \rho U_f D_h/\mu$, and the average Nusselt number is the length-average of the local value.

2.3. Numerical method and boundary conditions

The simulations are performed in ANSYS Fluent, where the governing equations are solved by the finite volume method with second-order upwind discretization of the momentum and energy equations. Its magnetohydrodynamic (MHD) module models the interaction between the electromagnetic field and the conducting fluid. A constant heat flux is applied to the base of the heat sink and the heat sink walls are insulated. The fluid enters with temperature T_f and velocity U_f, the outlet is a pressure outlet, and all walls are electrically conducting when the magnetic field is applied. A grid independence study with three grids (440,000, 912,000 and 2,290,000 cells) at an inlet velocity of 0.4 m/s and a heat flux of 10 W/cm² is given in Table 1. The grid with 912,000 cells was selected because further refinement changes the heat transfer coefficient by only 0.09%.

Table 1. Grid independence study

Number of cells	Maximum velocity (m/s)	h (W/m²·K)	Relative difference (%)
440,000	0.609	56,134	–
912,000	0.626	56,412	0.5
2,290,000	0.629	56,465	0.09

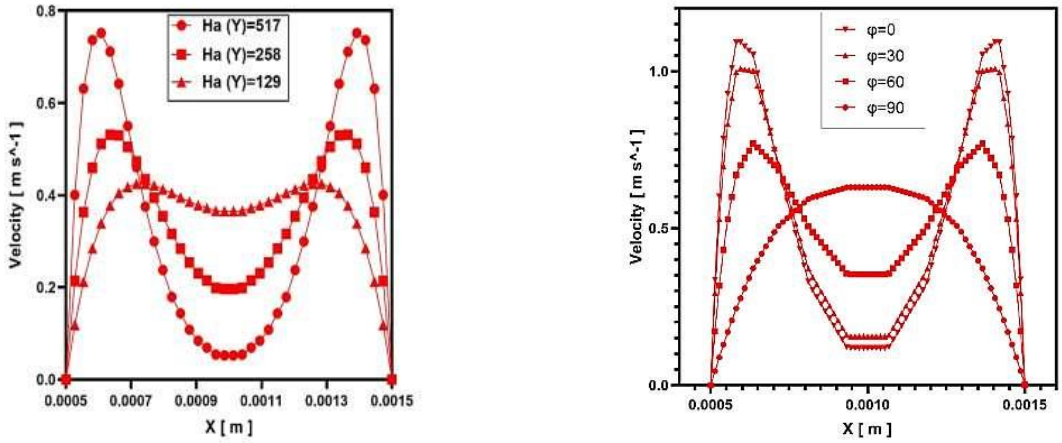
3. Results and Discussion

3.1. Validation

For validation, liquid metal under magnetic fields of 0.1 and 0.06 T in a rectangular microchannel with a constant wall temperature and electrically conducting walls was simulated and compared with Wang and Lei [8]. The velocity profile (at y = 0.01 m) shows a higher velocity near the walls and a lower velocity at the center, which is characteristic of Hunt flow [10], and the predicted temperature distribution agrees well with the reference results.

3.2. Direct magnetic field

A direct field in the Y direction produces a Lorentz force opposing the flow. As the Hartmann number increases (Ha = 129, 258, 517), the velocity profile departs from the uniform shape and becomes M-shaped (Figure 2a): the velocity increases near the walls and decreases along the channel centerline. Under constant heat flux, the higher near-wall velocity lowers the heat sink surface temperature and improves the Nusselt number (U = 0.3 m/s). However, because of the no-slip condition, the larger wall velocity gradient increases the friction coefficient and the pressure drop.



(a) **(b)**

Figure 2. Velocity distribution across the microchannel for a field in the Y direction: (a) direct field at different Hartmann numbers (U = 0.3 m/s), (b) alternating field at different phase differences (Ha = 517, U = 0.45 m/s)

3.3. Alternating magnetic field and phase difference

When the phase difference φ between the magnetic and electric fields is zero, their maxima coincide and the time-averaged Lorentz force is largest. At φ = 90° one field is at its maximum when the other is at its minimum, so the time-averaged force tends to zero and the velocity profile returns to the no-field shape; Figures 2b and 3 show the M-shaped profile of the Y-direction field returning to the uniform shape as φ increases. An alternating field in the X direction gives a flatter profile. In both cases the near-wall velocity rises, the surface temperature decreases and the Nusselt number improves relative to the no-field case, by 38% for the Y direction and by 11.62% for the X direction.

As φ increases up to 90°, the pressure drop and friction coefficient decrease, while the Nusselt number decreases only slightly compared with φ = 0°. For the Y direction, the optimum φ = 60° reduces the pressure drop by 64%. For the X direction, the Nusselt number does not decrease significantly up to φ = 60°, while the pressure drop falls by 49%.

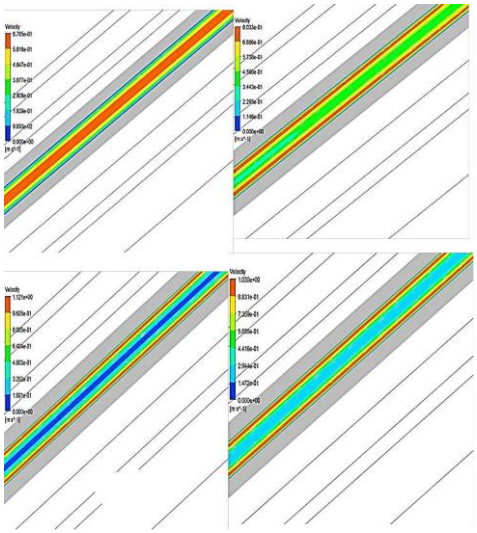


Figure 3. Velocity contours for an alternating field in the Y direction with increasing phase difference.

4. Conclusions

In this study, the effects of direct and alternating magnetic fields on the flow and heat transfer of Galinstan in a heat sink microchannel were numerically investigated. The main findings are:

- **Velocity distribution:** A direct or alternating field in the Y direction creates an M-shaped velocity profile (high near-wall velocity, low centerline velocity), while an alternating field in the X direction produces a flatter profile. Both lower the heat sink surface temperature.
- **Heat transfer:** At *Ha* = 517, an alternating field improves the Nusselt number by 38% in the Y direction and by 11.62% in the X direction.
- **Pressure drop:** The larger velocity gradient increases the friction coefficient and pressure drop, which rises sharply with the Hartmann number under a direct field.
- **Phase difference:** Increasing φ from 0 to 90° weakens the time-averaged Lorentz force and reduces the pressure drop and friction coefficient. The optimum φ = 60° reduces the pressure drop by 64% (Y) and 49% (X) with only a small Nusselt number penalty, improving overall performance and reducing pumping energy consumption.

Future work should seek further ways to reduce the magnetic pressure-drop penalty.

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