J. Energy Conversion (JEED)
Volume: 12, Issue:1, 2025: 43-65

نشریه علمی-تخصصی تبدیل انرژی

دوره ۱۲، شماره ۱، بهار ۱۴۰۴، ص: ۶۵-۴۳

Numerical investigation of the effect of using different ferrofluids under the effect of magnetic dipoles with different strengths on heat transfer and pressure drop in a two-dimensional channel

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Received: Winter 2025 Accepted: Spring 2025

Extended Abstract

Introduction and Problem Statement

Ferrofluids have attracted significant attention in recent years due to their tunable flow and heat transfer characteristics under the influence of external magnetic fields. These smart fluids, consisting of magnetic nanoparticles dispersed in a base fluid, offer promising potential for enhancing thermal performance in heat exchangers, cooling systems, and energy-related applications. However, the complex interaction between magnetic forces, fluid flow, and heat transfer necessitates detailed numerical investigations.

Physical Model and Assumptions

In the present study, a numerical analysis was conducted to investigate the coupled flow and heat transfer behavior of a ferrofluid subjected to an external magnetic field. The ferrofluid was modeled as a two-phase medium comprising a base fluid and uniformly dispersed magnetic nanoparticles. Effective thermophysical properties were evaluated using established theoretical correlations, while particle agglomeration, sedimentation, and slip effects were assumed negligible. The flow was considered laminar, two-dimensional, steady, and incompressible. The governing equations accounted for viscous effects, thermal conduction, and magnetic body forces. A controlled magnetic field was imposed, and its influence on the flow structure and thermal behavior of the ferrofluid was systematically examined.

Governing Equations and Boundary Conditions

The continuity, momentum, and energy equations were employed to describe the system. Magnetic body forces were incorporated as source terms in the momentum equations, while the dependence of fluid properties on nanoparticle volume fraction was included in the formulation. Appropriate hydrodynamic and thermal boundary conditions were applied at the walls and flow boundaries, allowing for heat exchange between the ferrofluid and solid surfaces.

Numerical Method and Validation

The governing equations were solved using the finite volume method. Pressure–velocity coupling was achieved through an appropriate algorithm, and strict convergence criteria were enforced to ensure numerical stability and accuracy. Grid independence tests were performed to minimize discretization errors. The numerical model was validated by comparing the present results with reference data available in the literature, demonstrating good agreement and confirming the reliability of the computational approach.

Results and Discussion

In the present study, the hydrodynamic and thermal behavior of different ferrofluids flowing laminarly inside a channel was investigated under both magnetic-field-free and magnetic field conditions. The results indicate that increasing the volume fraction of iron oxide nanoparticles enhances heat transfer performance and increases the Nusselt number; however, it simultaneously leads to a significant rise in pressure drop and required pumping

power. In the absence of a magnetic field, ferrofluids with higher nanoparticle concentrations exhibit superior thermal performance due to their higher effective thermal conductivity, at the expense of increased pressure losses.
When a non-uniform magnetic field generated by a magnetic dipole is applied, the flow structure and temperature distribution are substantially altered. The temperature difference between the cooler core flow and the hotter near-wall regions results in non-uniform magnetic forces, which induce flow deviation, vortex formation, and the emergence of thermally favorable and unfavorable regions. Although this mechanism enhances local heat transfer, the associated increase in pressure drop often limits the overall thermal–hydraulic efficiency of the system.The application of two magnetic fields with different strengths further intensifies flow vortices and improves cooling performance, particularly for ferrofluids with higher magnetic nanoparticle content. Nevertheless, the resulting pressure drop and pumping power increase considerably, emphasizing the necessity of balancing heat transfer enhancement against hydraulic penalties. The findings reveal that ferrofluids with moderate nanoparticle volume fractions provide a more balanced thermal–hydraulic performance.
Moreover, the location of magnetic dipoles plays a critical role in system performance. Positioning the magnetic field closer to the channel inlet significantly increases the pressure drop, whereas shifting it downstream reduces the inlet pressure. Under specific configurations, a notable enhancement in heat transfer can be achieved with only a minor increase in pressure drop, identifying these arrangements as optimal operating conditions.

Conclusion

Increasing the nanoparticle volume fraction enhances heat transfer but increases pressure drop. Applying a magnetic field improves the average Nusselt number for all ferrofluids, while the pressure penalty strongly depends on magnetic strength and dipole arrangement. Dual magnetic dipoles provide the highest thermal enhancement at the expense of higher pressure losses. An optimized combination of ferrofluid properties and dipole positioning enables significant heat transfer improvement with minimal hydraulic penalty.

Key words: Ferrofluid, Nusselt Number, Magnetic Dipoles, Two Dimensional Channel, Heat Transfer

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Cite this article as: Mahziyar Ghaedi1, Hamid-Reza Bahrami, Numerical investigation of the effect of using different ferrofluids under the effect of magnetic dipoles with different strengths on heat transfer and pressure drop in a two-dimensional channel. **Journal of Energy Conversion, 2025, 12(1), 43-65**.