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Numerical Study of Nanofluid-Based Cooling in Porous-Finned Enclosures

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Extended Abstract

Thermal management remains a critical challenge in compact, high-power electronic devices, where conventional cooling methods that use base fluids often prove inadequate. This study proposes a numerical investigation of laminar mixed convection in cubical enclosures integrating nanofluids, porous media, and solid fins to enhance heat dissipation. The work employs an in-house computational code in C, solving the biharmonic formulation of the Navier-Stokes equations on a nonuniform grid [1] to resolve complex flow and thermal interactions between multiple domains: a nanofluid (e.g., Al_2O_3/water), a porous base layer, and three vertically mounted solid fins coated with porous material.

Nanofluids, suspensions of nanoparticles typically consisting of 100-1000 atoms dispersed in base fluids, exhibit enhanced thermal conductivity with a reduced likelihood of microchannel clogging due to their sub-micron scale [2]. In addition, their lower particle momentum minimizes erosion risks compared to larger additives [3]. The thermophysical properties essential for modelling nanofluid behaviour, such as thermal conductivity and viscosity, are derived from established correlations that consider variations in particle size, concentration, and temperature [3]. These properties are crucial for simulations aimed at optimizing heat transfer while reducing the flow resistance caused by viscosity.

The solver addresses conjugate heat transfer across fluid, porous, and solid zones under thermal equilibrium conditions. Active cooling was modelled via inlet/outlet flow, whereas the biharmonic approach improved the numerical stability for high Reynolds and Richardson number flows. A nonuniform grid ensures precise resolution of the boundary layers near fins and porous interfaces. Key parameters include nanoparticle concentration (0-5% vol.), porous permeability (Darcy number: 10^{-5}-10^{-2}), and fin geometry. The study evaluates heat transfer rates, velocity fields, and entropy generation to assess thermodynamic efficiency.

The findings of this research enhance our understanding of how nanofluids interact with porous-finned structures to optimize thermal performance. By substituting traditional fluids [4] with nanofluids, we anticipate that the increased thermal conductivity and micro convection driven by nanoparticles will significantly improve heat transfer. The biharmonic formulation specifically addresses the coupling of stream function and velocity in multi-domain systems, while entropy analysis effectively quantifies the irreversible losses associated with heat exchange, fluid friction, and the influence of nanoparticles. This will help us build more effective cooling by establishing an optimal balance between nanoparticle loading (to prevent viscosity penalties) and fin-porous designs (to enhance surface area utilization).

This study introduces a novel computational framework that significantly improves the modelling of conjugate heat transfer in heterogeneous media, providing important insights into the interactions between nanofluids and porous materials, a topic that has been rarely explored in prior studies. Future initiatives will focus on validating these simulations against benchmark cases and experimental data, with applications to electronics, energy systems, and aerospace thermal management.

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