

Software simulation of magnetohydrodynamic cooling flow in curved porous fusion reactor channels

Hassan Mohammad Hassan, Liqaa Zeki Hummady

Department of Mathematics, College of Science, University of Baghdad, Baghdad, Iraq

Article Info

Article history:

Received Apr 24, 2026

Revised Aug 11, 2026

Accepted Sep 11, 2026

Keywords:

Curved porous channel
Embedded simulation
Finite-difference method
Magnetohydrodynamics
Pb-17Li+AlN nanofluid
Reconfigurable monitoring

ABSTRACT

This paper presents a numerical simulation of the hydrodynamic magnetoelectric cooling flow in a curved porous reactor channel. The research aims to evaluate the interrelated effects of channel curvature, porous resistivity, magnetic damping, and heat transfer on the hydrodynamic and thermal behavior of the candidate reactor chillers. The mass, momentum, pressure gradient, and energy equations were formulated in a curvature-compatible coordinate system. Porous resistivity was represented using the Darcy-Brinkman-Forchheimer model, while the magnetic interaction was incorporated through a quasi-static magnetohydrodynamic (MHD) approximation. The resulting interrelated equations were solved in MATLAB R2025b using the finite-difference fractionation method and iterative solution. Four chillers were examined within the same geometric and numerical framework: water, helium, Pb-17Li, and a Pb-17Li+AlN nanofluid. The results show that curvature and porous resistivity modify the velocity distribution and increase the pressure gradient requirements, while magnetic damping contributes to the stability of the conductive flows by inhibiting secondary motion. The thermal results indicate that the Pb-17Li+AlN nanofluid improves heat transfer behavior compared to base coolants, despite its high hydraulic resistance. The proposed simulation framework could support future internet of thing (IoT)-enabled integrated reactor cooling monitoring systems.

This is an open access article under the [CC BY-SA](#) license.



Corresponding Author:

Hassan Mohammad Hassan

Department of Mathematics, College of Science, University of Baghdad

Baghdad, Iraq

Email: hasan.hasan2303@sc.uobaghdad.edu.iq

1. INTRODUCTION

Fusion is generally considered to be one of the most attractive long-term energy sources, with a potential to offer sustainable, carbon free electricity on a large scale with attractive supply chain and operational safety. The cooling system is, therefore, one of the critical subsystems of a fusion reactor, which has a decisive effect on maintaining structural integrity of reactor components, prevention of plasma-facing components (PFCs) damage and stable reactor operation under intense nuclear heating. As such, liquid-metal coolants have been the subject of intense interest, due to their superior thermal properties, such as high thermal conductivity and volumetric heat capacity, as well as their ability to withstand extreme environments as those found in advanced fusion reactors. However, a challenge remains in terms of removing heat efficiently with an acceptable hydraulic performance, and this is especially difficult when the flow is dominated by the effects of more than one of the following: very complicated channel configurations, porous media, and externally applied magnetic fields [1]–[3].

In practical fusion reactor cooling blankets, the coolant almost never flows in straight, clear channels. Rather it is typically flowed through curved ducts with porous inserts or porous structural materials, aimed at enhancing heat dissipation and mechanical stiffness. As a result, under these extreme conditions, the interplay between centrifugal forces induced by the channel curvature, viscous effects within the porous media and magnetohydrodynamic (MHD) damping due to the presence of strong magnetic fields leads to highly coupled transport processes that cannot be modeled accurately with reduced hydrodynamic models. These synergistic effects modify the velocity profiles, the pressure losses and the thermal transfer properties, and so the prediction of the coolant capability becomes much more elusive. Therefore, designing full numerical models that can simultaneously consider curvature, porous resistance and magnetic effects has gained more importance in the design, and the optimization of cooling systems for fusion reactors.

Detailed parts of these transport processes have been the subject of intense investigations. Early studies led to the prediction of basic state patterns of such fluids and confirmed the importance of Lorentz forces for momentum transportation and flow stabilization [4], [5]. Classical results on curved-channel hydrodynamics also prove that curvature induces secondary flow and alters the velocity profile via the action of centrifugal forces, impacting the distribution of pressure and consequently, the total energy of the flow [6], [7]. Meanwhile, transport in porous media has been extensively studied under Darcy, Brinkman and Forchheimer (for both viscous diffusion and inertial resistance) terms for various types of permeable media [8]–[12]. Further research has generalized these ideas to MHD heat-transfer problems and has underscored the need to consider thermal transport, pressure losses, and magnetic dampening concurrently in high-temperature liquid-metal coolants systems [13]–[20].

While these research works provided substantial contributions in MHD flows, curved-channel transport and porous-medium modelling, the majority of the previously reported studies on these physical mechanisms have been conducted either separately or on a few, elementary coupled versions of them. Thus, the effect of channel curvature, porous resistance, magnetic damping, pressure evolution, and heat transfer has yet to be thoroughly investigated in a single numerical scheme in a manner to examine the performance of various fusion-relevant coolants at the same operating conditions [21], [22].

To overcome these issues, in this work, a coupled finite-difference simulation methodology is established to investigate MHD flow and heat transfer in a two-dimensional curved porous cooling channel of the fusion reactor blanket system. Rather than isolated physical mechanisms, as in earlier papers, the model considers channel curvature, Brinkman viscous diffusion, Darcy permeability, Forchheimer inertial resistance, Lorentz-force damping, pressure evolution, and convective heat transfer all at once in a single computational formulation. The numerical realization is done in MATLAB, allowing for the computational efficiency needed to maintain numerical stability while systematically studying the coupled transport processes under the same operating conditions. In addition, the framework that is introduced here is used to predict and compare the thermo-hydraulics performance of a number of potential coolants for fusion applications such as water, helium, Pb-17Li, and Pb-17Li enhanced with AlN nanoparticles [23], [24].

Hence, the main novelty brought by this work resides in the fact that an overarching numerical model has been introduced allowing a number of physical effects, usually treated separately in the most recent literature, to be combined in one single simulation tool. This holistic formulation allows the concurrent prediction of velocity, pressure, and temperature distributions and also provides a common underpinning for the assessment of coolant performance in an actual fusion reactor environment. The novel unified solution facilitates a better insight of the complicated phenomenon of magnetic damping competing with porous resistance in a curved channel, and hence, enables better coolant preparation and channel design in more advanced fusion energy systems [25].

In addition to its numerical value, the applicability of the proposed computational framework is with reconfigurable and embedded systems. The finite-difference scheme developed in this work is a computational kernel that can be ported to embedded monitoring platforms, digital twin environments, and real-time thermal management solutions for fusion reactors. With fast prediction of thermo-hydraulic performance based on the tested operating condition, the approach can enable intelligent monitoring, fault diagnosis, and predictive control strategies with internet of thing (IoT)-enabled sensing infrastructures. In addition, the algorithm is also hardware-friendly, allowing for the possibility of being mapped on hardware accelerators such as field-programmable gate array (FPGA) and very-large-scale integration (VLSI)-based embedded systems for real-time reactor supervision and adaptive coolant control [26]–[28].

Accordingly, this study provides both scientific and engineering contributions by combining advanced multiphysics modelling with computational techniques that are compatible with future intelligent reactor monitoring architectures. The developed methodology establishes a flexible numerical platform for evaluating coolant behaviour in fusion reactor cooling systems while simultaneously contributing toward the development of embedded decision-support technologies for next-generation nuclear energy applications. The remainder of this paper is organized as follows. Section 2 presents the physical model and governing equations. Section 3 describes the numerical method and computational procedure. Section 4 discusses the

numerical results and their physical interpretation, whereas section 5 summarizes the principal conclusions and outlines directions for future research.

2. PHYSICAL MODEL AND GOVERNING EQUATIONS

2.1. Geometry and coordinate system

The domain of the computational fluid mechanics problem we will be solving here is a curved two-dimensional porous channel in polar coordinates (r, s) . The r -coordinate represents the radial coordinate through the channel thickness emanating from the inner wall of the channel ($r = 0$) and reaching the outer wall (r_{max}). The s -coordinate takes on values along the curve tangentially and follows the path of the vector field streamlines along the main flow.

The radius of curvature of the channel was found to be constant at R and is consistent with classical studies of curved channel flows [6], [7]. On this basis, the apparent local radius in the governing equations can be taken as $(R + r)$, which clearly accounts for radial variation across the thickness of the channel, and automatically considers the centrifugal effect of curvature.

For improved fluid-solid interaction and heat transfer, a porous structure was considered within the channel as would be appropriate for many fusion reactor cooling configurations [8], [9]. The use of a polar coordinate system allows us to directly relate the channel curvature directly and avoid needing the curvature approximation of the source boundary that is done in Cartesian coordinates. This also ensures that hydrodynamic interactions are consistently treated in a curved geometry without any loss in generality and recovers our porous channel boundary as $R \rightarrow \infty$ [16]–[18].

Figure 1 illustrates the physical configuration considered in the present work. Specifically, Figure 1(a) shows the representative fusion reactor cooling system, whereas Figure 1(b) presents the corresponding computational domain employed in the numerical simulations.

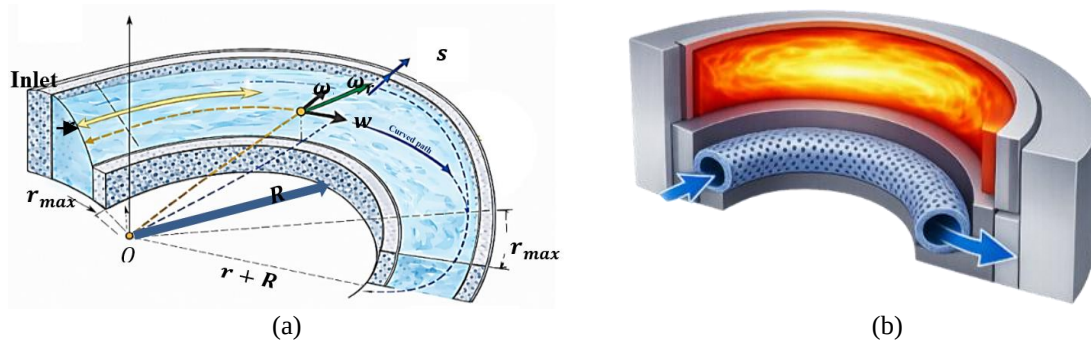


Figure 1. Schematic representation of the fusion reactor cooling configuration and computational domain; (a) computational porous channel with the adopted coordinate system and characteristic dimensions and (b) schematic illustration of the representative cooling channel location within a fusion reactor structure

2.2. Modeling assumptions and physical framework

Formulas for the system of equations governing the flow of an incompressible coolant at low Mach numbers relevant to fusion reactor cooling applications. Fluid density (ρ) and porosity (ϕ) were treated as constants, and volumetric mass sources were neglected to obtain a divergence-free velocity field [16]–[18].

The porous medium was represented using the Darcy-Brinkman-Forchheimer formulation, which takes into account the inertial resistance, viscous resistance, and shear effect near the wall within the porous matrix [8]–[12]. It was also assumed that the porosity is spatially uniform throughout the channel.

The effects of MHD are incorporated into a quasi-stationary approximation framework consistent with a magnetic Reynolds number (Re) and a defined external magnetic field. The Lorentz force is incorporated into the momentum equations, while Joule heating is retained in the heat equation to maintain energy consistency [13]–[15].

The mathematical model is a steady-state, laminar, incompressible, and two-dimensional MHD flow in a homogeneous porous medium in the presence of uniform transverse magnetic field. The finite-difference scheme is used to discretize the governing equations and is solved in MATLAB R2025b. In the following subsections, the computational domain and boundary conditions used are introduced, the thermophysical properties utilized in all simulations are presented.

2.3. Dimensional governing equations

For the physical model and assumptions outlined above, dimensional governing equations for incompressible flow and heat transfer in a curved porous channel are derived as follows in the (r, s) coordinate system [16]–[18]: flow: (w_r) and (w_s) ; p ; T ; incorporating effects of curvature via the local radius $(R + r)$, as defined in subsection 2.1. Under the incompressibility assumption adopted in this study, the continuity equation reduces to:

$$\frac{1}{r+R} \frac{\partial}{\partial r} ((r+R)w_r) + \frac{R}{r+R} \frac{\partial}{\partial s} (w_s) = 0 \quad (1)$$

The radial and tangential momentum equations are expressed as (2) and (3):

$$\rho \left(\frac{\partial w_r}{\partial t} + w_r \frac{\partial w_r}{\partial r} + \left(\frac{R}{r+R} \right) w_s \frac{\partial w_r}{\partial s} - \frac{w_s^2}{r+R} \right) = - \frac{\partial p}{\partial r} + \mu_{eff} \left[\frac{\partial^2 w_r}{\partial r^2} + \left(\frac{1}{r+R} \right) \frac{\partial w_r}{\partial r} + \left(\frac{R^2}{(r+R)^2} \right) \frac{\partial^2 w_r}{\partial s^2} - \frac{w_r}{(r+R)^2} \right] - \frac{\mu}{k} w_r - \rho \beta |w| w_r + \rho g_r + \sigma [B_r (w \cdot B) - B^2 w_r] \quad (2)$$

and

$$\rho \left(\frac{\partial w_s}{\partial t} + w_r \frac{\partial w_s}{\partial r} + \left(\frac{R}{r+R} \right) w_s \frac{\partial w_s}{\partial s} + \frac{w_r w_s}{r+R} \right) = - \frac{R}{r+R} \frac{\partial p}{\partial s} + \mu_{eff} \left[\frac{\partial^2 w_s}{\partial r^2} + \left(\frac{1}{r+R} \right) \frac{\partial w_s}{\partial r} + \left(\frac{R^2}{(r+R)^2} \right) \frac{\partial^2 w_s}{\partial s^2} - \frac{w_s}{(r+R)^2} \right] - \frac{\mu}{k} w_s - \rho \beta |w| w_s + \rho g_s + \sigma [B_s (w \cdot B) - B^2 w_s] \quad (3)$$

Accounting for transient, convective, and viscous effects. Resistance added by the porous medium through Darcy and Forchheimer drag terms while near-wall shear is retained via Brinkman contribution. The governing equations account for transient, convective, and viscous effects. Porous resistance is introduced through the Darcy and Forchheimer drag terms, while near-wall shear is retained through the Brinkman contribution [8]–[12]. MHD interactions are represented through the Lorentz-force term [13]–[15]. Curvature-induced inertial effects are introduced through the local radius $(R + r)$ [6], [7].

The pressure field is not prescribed explicitly but is obtained numerically from its spatial gradients:

$$\frac{\partial p}{\partial r} = -\rho \left[\frac{\partial w_r}{\partial t} + w_r \frac{\partial w_r}{\partial r} + \left(\frac{R}{r+R} \right) w_s \frac{\partial w_r}{\partial s} - \frac{w_s^2}{r+R} \right] + \mu_{eff} \left[\frac{\partial^2 w_r}{\partial r^2} + \left(\frac{1}{r+R} \right) \frac{\partial w_r}{\partial r} + \left(\frac{R^2}{(r+R)^2} \right) \frac{\partial^2 w_r}{\partial s^2} - \frac{w_r}{(r+R)^2} \right] - \frac{\mu}{k} w_r - \rho \beta |w| w_r + \rho g_r + \sigma [B_r (w \cdot B) - B^2 w_r] \quad (4)$$

and

$$\frac{R}{r+R} \frac{\partial p}{\partial s} = -\rho \left[\frac{\partial w_s}{\partial t} + w_r \frac{\partial w_s}{\partial r} + \left(\frac{R}{r+R} \right) w_s \frac{\partial w_s}{\partial s} + \frac{w_r w_s}{r+R} \right] + \mu_{eff} \left[\frac{\partial^2 w_s}{\partial r^2} + \left(\frac{1}{r+R} \right) \frac{\partial w_s}{\partial r} + \left(\frac{R^2}{(r+R)^2} \right) \frac{\partial^2 w_s}{\partial s^2} - \frac{w_s}{(r+R)^2} \right] - \frac{\mu}{k} w_s - \rho \beta |w| w_s + \rho g_s + \sigma [B_s (w \cdot B) - B^2 w_s] \quad (5)$$

ensuring consistency with mass conservation and momentum balance [16]–[19].

The energy equation governing heat transfer in the coolant is written as (6):

$$\left[(1 - \phi) \rho_s C_{p,s} + \phi \rho_f C_{p,f} \right] \frac{\partial T}{\partial t} + \rho_f C_{p,f} \left(w_r \frac{\partial T}{\partial r} + \frac{R}{r+R} w_s \frac{\partial T}{\partial s} \right) - \phi \alpha_f T \left(\frac{\partial p}{\partial t} + w_r \frac{\partial p}{\partial r} + \frac{R}{r+R} w_s \frac{\partial p}{\partial s} \right) = k_{eff} \left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r+R} \frac{\partial T}{\partial r} + \frac{R^2}{(r+R)^2} \frac{\partial^2 T}{\partial s^2} \right) + \frac{\partial k_{eff}}{\partial r} \frac{\partial T}{\partial r} + \frac{\partial k_{eff}}{\partial s} \frac{R^2}{(r+R)^2} \frac{\partial T}{\partial s} + \phi Q_{vol} + \phi Q_J + \phi \Phi_{viscous} \quad (6)$$

where heat transport by convection and conduction is considered. Volumetric heat generation and viscous dissipation are included where applicable, and Joule heating is kept for electrically conductive fluids under MHD conditions [13], [14], [20].

In (1)–(6) constitute a coupled system describing the transport of mass, momentum, pressure gradients, and energy in a curved porous channel subjected to hydromagnetic effects. The system is solved numerically subject to the boundary conditions specified in subsection 2.4.

2.4. Boundary conditions

The governing equations are solved in the (r, s) domain subject to the following dimensional boundary conditions. The streamwise coordinate s is aligned the main flow direction, with $(s = 0)$ denoting the inlet and $s = s_{max}$ at the outlet, while r is the transverse coordinate across the channel thickness, with $r = 0$ at the inner wall and $r = r_{max}$ at the outer wall.

Inlet ($s = 0$)

At the inlet, dirichlet boundary conditions are prescribed for the velocity components and temperature field:

$$\begin{aligned} w_r(r, 0) &= 0 \\ w_{s,in}(r) &= w_s(r, 0) \\ T_{in} &= T(r, 0) \end{aligned}$$

Here, $w_{s,in}(r)$ denotes a prescribed inlet velocity profile chosen to provide a well-defined reference state for the subsequent flow development [17]. The flow is driven by a constant streamwise pressure gradient:

$$\frac{\partial p}{\partial s} = G \text{ (constant)}$$

Which corresponds to a linear pressure variation along the channel [19]. To remove the arbitrary additive constant in the pressure field, a pressure reference is fixed at the outlet:

$$p(r, L) = p_{ref}$$

Outlet ($s = s_{max}$)

At the outlet, zero-gradient (outflow) conditions are applied to the transported variables:

$$\left. \frac{\partial w_r}{\partial s} \right|_{s=s_{max}} = 0, \left. \frac{\partial w_s}{\partial s} \right|_{s=s_{max}} = 0, \left. \frac{\partial T}{\partial s} \right|_{s=s_{max}} = 0$$

Allowing a smooth exit of the flow and thermal fields without imposing artificial constraints.

Solid walls, no-slip conditions are enforced at both channel walls:

$$w_r(0, s) = w_s(0, s) = 0, w_r(r_{max}, s) = w_s(r_{max}, s) = 0$$

Thermal boundary conditions: thermal conditions at the walls are prescribed as:

$$\left. \frac{\partial T}{\partial r} \right|_{r=0} = 0, \text{ (adiabatic inner wall)}$$

$$T(r_{max}, s) = T_w, \text{ (isothermal outer wall)}$$

These boundary conditions uniquely specify the velocity, pressure-gradient-driven flow, and temperature fields, and ensure a well-posed thermohydrodynamic problem for the curved porous channel under hydromagnetic conditions.

2.5. Non-dimensional formulation and governing parameters

To reduce the governing equations to a dimensionless form and to identify the controlling physical mechanisms, the following reference scales are introduced: the transverse length scale r_{max} , the streamwise length scale L_s , a characteristic velocity w_0 , the time scale $t_0 = L_s/w_0$, the pressure scale $= p_0 \rho_0 w_0^2$, and the temperature scale ΔT . The dimensionless variables are defined as:

$$\begin{aligned} r &= L_r r^*, s = L_s s^*, w_r = w_0 w_r^*, w_s = w_0 w_s^*, t = t^* L_r / w_0, \rho = \rho_0 \rho^*, \\ P &= \rho_0 U^2 P^*, g_r = g_0 g^*, |w| = w_0 |w^*|, B = B_0 B^*, \Theta = \frac{T - T_{ref}}{\Delta T}, k_{eff} = k_0 k_{eff}^* \end{aligned}$$

The geometric curvature enters the formulation through the local radius $(r + R)$. In dimensionless form, this quantity appears as:

$$r_a^* = \frac{r+R}{R}, r_b^* = \frac{r+R}{L_r}, r_c^* = \frac{r+R}{RL_r}$$

Which is retained explicitly in the governing equations to account for curvature-induced centrifugal effects.

Continuity constraint, under the incompressibility assumption and constant porosity (ϕ), the continuity equation reduces to a divergence-free constraint on the velocity field:

$$\frac{1}{r_a^*} \frac{\partial}{\partial r^*} (r_a^* w_r^*) + \frac{L_r}{L_s} \frac{1}{r_a^*} \frac{\partial}{\partial s^*} (w_s^*) = 0 \quad (7)$$

This relation represents conservation of mass in the porous curved channel. Substituting the above scalings into the dimensional Brinkman–Forchheimer–MHD momentum equations, the non-dimensional momentum equations in the radial (r) and tangential (s) directions are written as:

a. Radial momentum equation

The convergence of the numerical solution is checked by using the calibrated residuals of the velocity and temperature fields. Iterations are stopped when the residual values of the dependent variables were within the specified tolerance, and there was no significant change in the contour lines or profiles of the calculated lines. The use of partial attenuation improved the robustness of the iteration process, especially in cases of strong Forchheimer resistance or high magnetic interaction.

A zero-gradient output condition was:

$$\rho^* \left[\frac{\partial w_r^*}{\partial t^*} + w_r^* \frac{\partial w_r^*}{\partial r^*} + \frac{L_r}{L_s} \frac{w_s^*}{r_a^*} \frac{\partial w_r^*}{\partial s^*} - \frac{L_r}{R} \frac{w_s^{*2}}{r_a^*} \right] = -\frac{\partial p^*}{\partial r^*} + \frac{1}{Re_B} \left[\frac{\partial^2 w_r^*}{\partial r^{*2}} + \frac{L_r}{R} \frac{1}{r_a^*} \frac{\partial w_r^*}{\partial r^*} + \frac{L_r^2}{L_s^2} \frac{1}{r_a^{*2}} \frac{\partial^2 w_r^*}{\partial s^{*2}} - \frac{L_r^2}{R^2} \frac{w_r^*}{r_a^{*2}} \right] - \frac{1}{Re Da} w_r^* - \frac{Fo}{U} \rho^* |w^*| w_r^* + Fr \rho^* g^* + N [B^* (w^* \cdot B^*) - B^{*2} w_r^*] \quad (8)$$

Tangential momentum:

$$\rho^* \left[\frac{\partial w_s^*}{\partial t^*} + w_r^* \frac{\partial w_s^*}{\partial r^*} + \frac{1}{L_s} \frac{w_s^*}{r_c^*} \frac{\partial w_s^*}{\partial s^*} - \frac{1}{R} \frac{w_r^* w_s^*}{r_c^*} \right] = -\frac{1}{L_s r_c^*} \frac{\partial p^*}{\partial s^*} + \frac{1}{Re_B} \left[\frac{\partial^2 w_s^*}{\partial r^{*2}} + \frac{1}{R} \frac{1}{r_c^*} \frac{\partial w_s^*}{\partial r^*} + \frac{1}{L_s^2} \frac{1}{r_c^{*2}} \frac{\partial^2 w_s^*}{\partial s^{*2}} - \frac{1}{R^2} \frac{w_s^*}{r_c^{*2}} \right] - \frac{1}{Re Da} w_s^* - \frac{Fo}{U} \rho^* |w^*| w_s^* + Fr \rho^* g^* + N [B^* (w^* \cdot B^*) - B^{*2} w_s^*] \quad (9)$$

These equations are parameterized by viscous and inertial effects through the Brinkman Reynolds number (Re_B), porous resistance through the contributions of the Darcy and Forchheimer (β_F), and hydromagnetic effects through the interaction parameter (stuart number) N. The curvature effect is kept explicitly through the local radius (r_c^*).

b. Pressure-gradient relations

The pressure field appears in the formulation through its spatial gradients, which are obtained consistently from the momentum balances.

Radial pressure gradient:

$$\frac{\partial p^*}{\partial r^*} = -\rho^* \left[\frac{\partial w_r^*}{\partial t^*} + w_r^* \frac{\partial w_r^*}{\partial r^*} + \frac{L_r}{L_s} \frac{w_s^*}{r_a^*} \frac{\partial w_r^*}{\partial s^*} - \frac{L_r}{R} \frac{w_s^{*2}}{r_a^*} \right] + \frac{1}{Re_B} \left[\frac{\partial^2 w_r^*}{\partial r^{*2}} + \frac{L_r}{R} \frac{1}{r_a^*} \frac{\partial w_r^*}{\partial r^*} + \frac{L_r^2}{L_s^2} \frac{1}{r_a^{*2}} \frac{\partial^2 w_r^*}{\partial s^{*2}} - \frac{L_r^2}{R^2} \frac{w_r^*}{r_a^{*2}} \right] - \frac{1}{Re Da} w_r^* - \frac{\beta_F}{U} \rho^* |w^*| w_r^* + Fr \rho^* g^* + N [B^* (w^* \cdot B^*) - B^{*2} w_r^*] \quad (10)$$

Tangential pressure gradient:

$$\frac{1}{L_s r_c^*} \frac{\partial p^*}{\partial s^*} = -\rho^* \left[\frac{\partial w_s^*}{\partial t^*} + w_r^* \frac{\partial w_s^*}{\partial r^*} + \frac{1}{L_s} \frac{w_s^*}{r_c^*} \frac{\partial w_s^*}{\partial s^*} - \frac{1}{R} \frac{w_r^* w_s^*}{r_c^*} \right] + \frac{1}{Re_B} \left[\frac{\partial^2 w_s^*}{\partial r^{*2}} + \frac{1}{R} \frac{1}{r_c^*} \frac{\partial w_s^*}{\partial r^*} + \frac{1}{L_s^2} \frac{1}{r_c^{*2}} \frac{\partial^2 w_s^*}{\partial s^{*2}} - \frac{1}{R^2} \frac{w_s^*}{r_c^{*2}} \right] - \frac{1}{Re Da} w_s^* - \frac{\beta_F}{U} \rho^* |w^*| w_s^* + Fr \rho^* g^* + N [B^* (w^* \cdot B^*) - B^{*2} w_s^*] \quad (11)$$

These relations ensure a consistent coupling between pressure and velocity in the curved coordinate system.

Non-dimensional energy equation, the dimensionless energy equation governing heat transfer in the porous curved channel is written as (12):

$$Pe_m \frac{\partial \theta}{\partial t^*} + Pe_f \left(w_r^* \frac{\partial \theta}{\partial r^*} + \frac{1}{L_s} \frac{w_s^*}{r_c^*} \frac{\partial \theta}{\partial s^*} \right) = k_0 \left(\frac{\partial^2 \theta}{\partial r^{*2}} + \frac{1}{r_b^*} \frac{\partial \theta}{\partial r^*} + \frac{1}{L_s^2} \frac{1}{r_c^{*2}} \frac{\partial^2 \theta}{\partial s^{*2}} \right) + \frac{k_0}{k_{eff}} \frac{\partial k_{eff}^*}{\partial r^*} \frac{\partial \theta}{\partial r^*} + \frac{k_0}{k_{eff} L_s^2} \frac{\partial k_{eff}^*}{\partial s^*} \frac{\partial \theta}{\partial s^*} + \phi \Omega_{vol} + \phi Br_J + \phi Br_v L_r^2 + \phi \alpha_f T Ec Pe_m \left(\frac{\partial p^*}{\partial t^*} + w_r^* \frac{\partial p^*}{\partial r^*} + \frac{1}{L_s} \frac{w_s^*}{r_c^*} \frac{\partial p^*}{\partial s^*} \right) \quad (12)$$

Heat transfer by convection and diffusion is controlled by the Peclet numbers for the mixture and the fluid (Pe_m, Pe_f). Viscous dissipation and Joule heating are represented by the corresponding Eckert (Ec) and Brinkman numbers (Br). Pressure-work and dissipation terms are kept ensuring thermodynamic consistency under strong hydromagnetic and porous influences.

c. Governing dimensionless parameters

In (7)–(12) constitute a closed, coupled, non-dimensional system describing momentum transport, pressure-gradient-driven flow, and heat transfer in a curved porous channel under hydromagnetic conditions. The dimensionless groups arising from the above scaling include the Brinkman Reynolds number Re_B , Darcy number (Da), Forchheimer number β_F , Froude number Fr , interaction parameter (Stuart number) N , mixture and fluid Peclet numbers Pe_m and Pe_f , Eckert number Ec , viscous and Joule Brinkman numbers Br_v and Br_j , and the volumetric heat generation parameter Ω_{vol} . Their mathematical definitions and physical interpretations are provided in Table S1 of the supplementary material, following the standard conventions [16]–[21].

2.5.1. Parameter ranges and case setup

Due to the significant interdependence of camwheel thermophysical properties in the working fluids considered, identical values of dimensionless parameters are not expected to correspond to identical flow or thermal conditions. Hence for each coolant we will independently sample three representative levels for each influential dimensionless number to probe low, intermediate and high response regimes in physically realistic ranges.

Although the numerical values of the coefficients differ for each fluid, the number of responses remains constant for the same geometry/boundary conditions. This allowed us to assess the relative importance of properties/coefficients in absolute terms, and thus draw meaningful comparisons between water, helium, Pb-17Li and Pb-17Li+AlN nanofluid [22]–[24].

3. RESEARCH METHOD

Research approach was formulated on the basis of developing a software simulation technique for momentum coupling, pressure gradient, and heat transfer in a bent porous reactor cooling passage. The solution procedure for numerical simulation consisted of the following four steps: determination of channel geometry and coolant properties, the discretization of the governing equations on a 2D structured grid, iterative solution of the coupled velocity and temperature fields, and the validation of the numerical solution by monitoring the convergence and conducting grid-independent tests. The simulation was performed using MATLAB R2025b software. The computational method formulated in this work can be directly implemented in embedded monitoring systems due to its modular finite-difference nature.

3.1. Numerical partitioning and solution procedures

3.1.1. Spatial discretization

The computational domain was discretized into ordered elements of the diagonal and longitudinal directions using an ordered grid of $N_r \times N_s$ nodes. The diagonal coordinate r is for the transverse direction across the thickness of the porous channel, while the longitudinal coordinate s is the curved flow path. The spatial derivatives in the momentum, pressure gradient, and energy equations were taken finite-difference forms to approximate as in [19], [20]. The center difference approximations were used at diffusion boundaries, and convection boundaries were treated by a biased stable differential formula to minimize nonphysical oscillations under high inertia, pore resistance, and hydromagnetic dynamics [19]. The boundary conditions of subsection 2.4 were applied directly to the boundary nodes.

3.1.2. Iterative coupling strategy

For each chiller and parameter set, the momentum equations were solved considering the pressure gradient to obtain the radial and tangential velocity components. The velocity field in the energy equation was used to calculate the temperature distribution. The hydrodynamic and thermal solutions were coupled through an external iterative loop since the energy equation had convection, diffusion, atmospheric heating, viscosity dissipation, and volumetric heat generation boundaries [19], [20]. Deviation mitigation was applied in those cases where it was needed to ensure that the solution remained monotonically convergent and hence avoided any numerical instability that might arise due to the combined effects of curvature, pore resistance, and magnetic damping.

The numerical procedure applied in the simulation is briefly described as follows:

Step 1: Specify the channel geometry, properties of the coolant, parameters of the porous medium, parameter of the magnetic field, and the thermal boundary conditions.

Step 2: The governing equations are discretized in the r and s directions.

Step 3: Initialize the velocity, pressure gradient and temperature fields to the given values of inlet and boundary conditions.

Step 4: Apply iterative methods to solve the discretized radial and tangential momentum equations for a given radial position.

Step 5: Determine the pressure gradient relations by the convergent momentum equilibrium equation.

Step 6: Compute the solution of the discretized energy equation with the initialized velocity and the pressure gradient fields.

Step 7: Repeat the two-solution procedure until both hydrodynamic and thermal residues meet the stipulated convergence criterion.

Step 8: Postprocess velocity, pressure, and temperature fields and contrast behavior for water, helium, Pb-17Li, and Pb-17Li+AlN nps.

3.1.3. Convergence and stability criteria

Convergence of the numerical solution was monitored with scaled residuals for the velocity and temperature fields. The iteration process ended with residuals under acceptable tolerance and when no significant changes in the contour field and line profiles were detected. Skew correction was applied if needed, to enhance the numerical stability, also for strong Forchheimer resistance or large magnetic interaction. Finally, a zero-gradient output condition was enforced so that the velocity and temperature fields could leave the computational domain as a normal outflow without artificial numerical straining.

3.1.4. Grid independence and numerical verification

We also tested grid independence to ensure that the calculated thermal response was not influenced by spatial resolution. Three structured grids of dimensions 40×80 , 60×120 , and 81×161 were tested under the same physical parameters and boundary conditions. As an indicator of grid convergence, the dimensionless temperature Θ at the mid-channel location (r_{mid} , s_{mid}) was chosen. Table 1 presents the results of the grid independence test. The difference between the 60×120 and 81×161 grids is almost negligible, showing that increasing the grid resolution has little effect on the selected thermal response. Therefore, we selected the 60×120 grid for use in later simulations because it provides a good balance between numerical accuracy and computational cost.

Table 1. Grid-independence study based on the dimensionless temperature Θ evaluated at the mid-channel location (r_{mid} , s_{mid})

Grid ($N_r \times N_s$)	$\Theta(r_{mid}, s_{mid})$	Relative difference (%)
40×80	$1.1288476266 \times 10^{-11}$	N/A
60×120	$1.1688476742 \times 10^{-11}$	3.42
81×161	$1.1688476970 \times 10^{-11}$	1.95×10^{-6}

3.2. Numerical verification and validation of the boundary state

The next numerical test was carried out to further confirm the reliability of the finite-difference simulation. The results of grid independence in Table 1 were used, first to estimate the relative dimensionless temperature variation in the middle of the channel between successive grid optimizations. The relative difference between 40×80 and 60×120 grids was about 3.42%; that between 60×120 and 81×161 grids was about $1.95 \times 10^{-6}\%$. This very small difference between the two finest grids confirms that the chosen 60×120 grid gives grid-independent results for the thermal field at a reasonable computational cost.

The second validation was done by studying the physical behaviour of the governing model when the curvature effect is weakened. In this case, the local radius boundary associated with the curved coordinate system tends toward the corresponding straight channel behaviour, and the effect of the centrifugal force on diagonal momentum equilibrium becomes less significant. It was also numerically proved that under weak bending conditions, there is a decrease in the radial velocity component compared to the tangential component, which is consistent with the expected decrease in secondary motion due to bending.

Third, the individual physical boundaries were checked by first reducing the main source boundaries in separate numerical experiments. The magnetic interaction coefficient was reduced, and this weakened the Lorentz force damping, while the conductive coolant was seen to have higher velocity [13]–[15]. Darcy-Forchheimer resistance boundaries were reduced to reflect the pressure gradient condition, wherein the resistance of the porous medium is reduced [8]–[12]. These boundary responses are in line with the physical roles of magnetic damping and porous drag in the governing equations.

Although a comprehensive comparison with commercial computational fluid dynamics software like ANSYS Fluent or COMSOL lies beyond the scope of the current software simulation, it does provide

numerical confidence in the applied model to test the network independence, boundary state behaviour, residual observation, and physical consistency checks for each boundary individually. Future work will expand the scope of the verification procedure by comparing the current finite-difference analyser with high-resolution computational fluid dynamics simulations and experimental data for reactor-related cooling channels.

4. RESULTS AND DISCUSSION

Herein, the numerical results are presented and discussed for the momentum fields, pressure gradient, and the related heat transfer in a curved porous cooling channel. The results are organized to demonstrate how the hydraulic and thermal response of the unit is affected by some of the dominant parameters. The first presentation displays the velocity, pressure, and temperature fields to reveal the main flow and heat transfer features. Further, the effect of parameters related to Reynolds number, Da, Forchheimer number, Stuart number, Eckert number, Peclet number, and volumetric heat generation number are discussed. The effects of coolant properties on the tradeoff among thermal performance, magnetic damping and pumping power (pressure gradient) are examined by considering water, helium, lead-17 lithium nanofluid, and lead-17 lithium nanofluid with aluminum nitride, and contrasting them with one another.

4.1. Effect of reynolds number

Figure 2 shows the influence of the Reynolds number Re on the tangential velocity component (w_s^*) along the flow line (s) at a typical radial position ($r=r_{mid}$). Three suggested Reynolds number values (15500, 15000, and 1600) were considered, and it was noted that the tangential velocity magnitude grows in the channel with the increment of the Reynolds number, suggesting that there is a progressive dominance of the inertial transportation over the viscosity dissipation inside the porous medium. This enhancement can be attributed to the inertial effect, is more pronounced in the downstream where [6]–[8] the inertial transport accumulates to yield stronger velocity gradients, which accounts for the strengthening of momentum loading along the curved flow path.

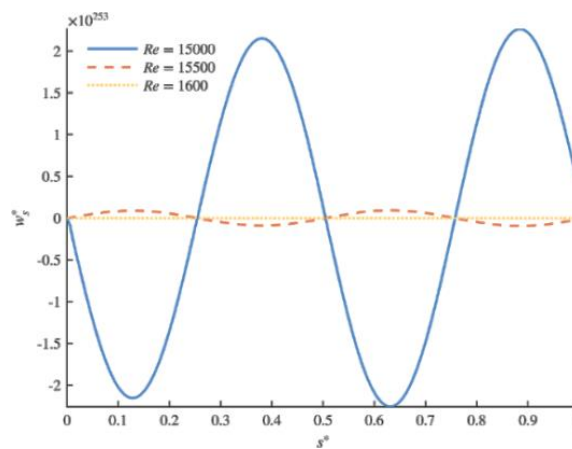


Figure 2. Influence of reynolds number on the dimensionless tangential velocity component along the flow direction w_s^*

Although not shown, the radial velocity increased slightly with Reynolds number because of stronger curvature-induced centrifugal effects, while the streamwise velocity remained dominant. As shown in Figure 3, increasing the Reynolds number also produced a steeper pressure gradient, reflecting the greater pressure required to overcome inertial, porous, and curvature-induced resistance. These results confirm that Reynolds number is a key parameter governing the hydraulic performance of the system and are consistent with the expected behavior of porous channels [8]–[12].

4.2. Effect of darcy number

Figure 4 shows that decreasing the Da, and hence the porous permeability, substantially increases the pressure gradient because of the stronger darcy resistance. This agrees with the Darcy-Brinkman formulation and indicates that low-permeability structures require greater pumping power to maintain the same coolant flow rate [8]–[12].

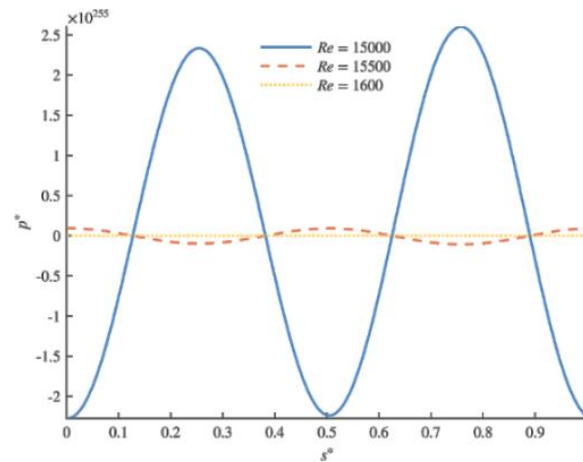


Figure 3. Effect of the Reynolds number on the pressure distribution along the flow direction at $r = r_{mid}$

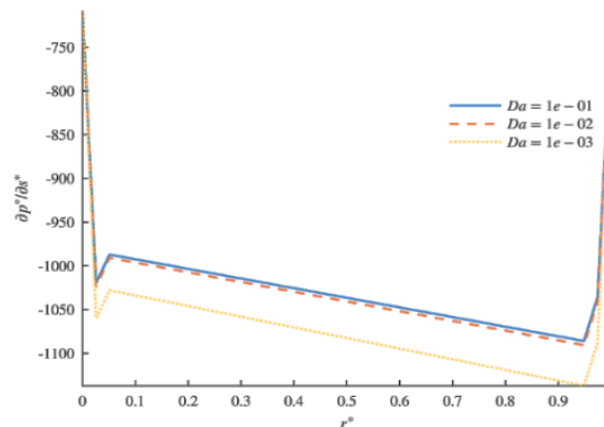


Figure 4. Effect of the Da on the dimensionless streamwise pressure gradient at a representative cross-section of the porous channel

4.3. Effect of forchheimer number

Figure 5 shows that increasing the Forchheimer number (β_F) strengthens nonlinear inertial resistance, thereby reducing the tangential velocity, particularly in the high-velocity central region. This behaviour follows from the quadratic dependence of Forchheimer drag on velocity and indicates increased hydraulic losses as inertial transport intensifies [8]–[12].

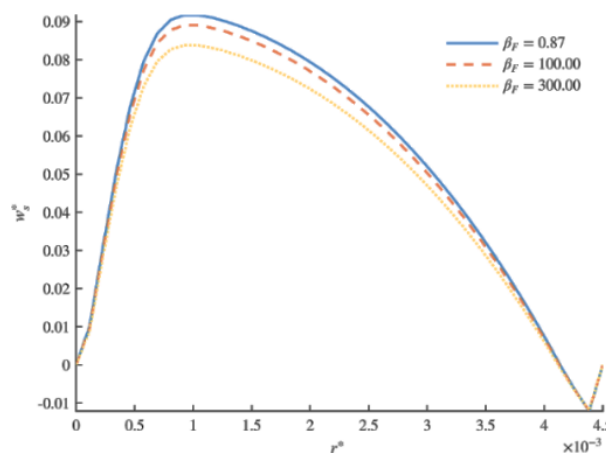


Figure 5. Effect of the forchheimer number β_F on the dimensionless tangential velocity profile w_s^* at $r = r_{mid}$ for the water case

Overall, increasing the forchheimer number enhances nonlinear porous resistance, thereby suppressing streamwise momentum transport and increasing the hydraulic losses that must be overcome to maintain the desired coolant flow rate.

4.4. Effect of stuart number

The effect of the stuart number N on the dimensionless tangential velocity component is presented in Figure 6, specifically the influence of magnetic (Lorentz) forces of damping inertial motion. As the Stuart number increases, so does the reduction in magnitude of the tangential velocity through the channel. This behaviour results from the intensified Lorentz force, which opposes the fluid motion and converts a larger fraction of the flow kinetic energy into electromagnetic damping. This corresponds to the effect of the Lorentz force producing greater and greater magnetic damping in the direction opposing that of the flow thus acting to lamina rise the inertial transport producing a weaker velocity field of magnetic dominance, perfectly fitting classical MHD behavior [13]–[15]. Thus, an increment in the Stuart number enhances the flow stabilization, but it needs to be appropriately optimized to prevent a severe decrease of the coolant transport capacity. In addition to reducing the streamwise velocity, increasing the Stuart number also intensified the associated pressure losses, reflecting the stronger electromagnetic resistance imposed on the flow.

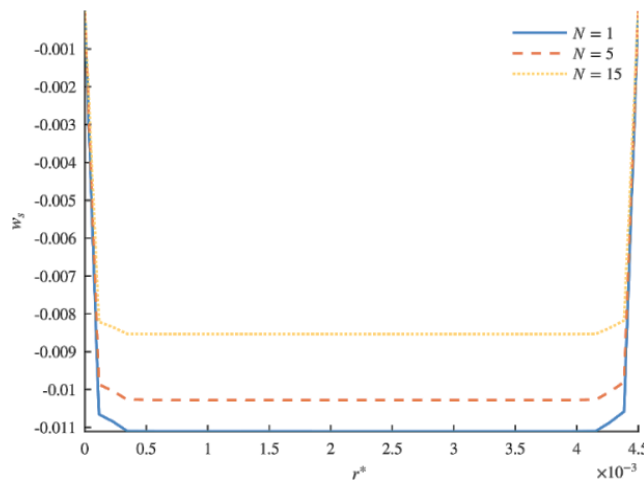


Figure 6. Effect of the Stuart number on the dimensionless tangential velocity component w_s^* at $r = r_{mid}$ for the electrically conductive Pb-17Li flow

4.5. Effect of eckert number

Effect of Eckert number (Ec) on flow of heat. The dependence of the heat flow process on viscous dissipation of energy is indicated by the Eckert number. The Eckert number characterizes the influence of viscous dissipation, representing the conversion of kinetic energy into internal energy through viscous effects [20].

Figure 7 represents the influence of Eckert number on the dimensionless temperature Θ along the tangential at a radius $r = r_{mid}$ for the Pb-17Li fluid. The curves for the three Eckert numbers tested are almost superimposed in the range studied and do not deviate significantly from the two higher Eckert's. This phenomenon suggests that the effect of the transformation of kinetic energy to thermal energy (the physical realization of Eckert number) is weak for realistic operating conditions. Consequently, the viscous dissipation term remains much smaller than the dominant energy transport mechanisms, particularly convective heat transfer and Ohmic heating. It is thus seen that, because of convection dominating at such high Peclet numbers, the Θ value is of small order in the middle region of the section, that is, a thin thermal layer is formed near the wall and the thermal effect does not penetrate to the center.

These results indicate that viscous dissipation has only a minor influence under the investigated operating conditions; therefore, thermal performance is governed primarily by convection and Joule heating. This finding provides useful guidance for optimizing coolant operating conditions in fusion reactor cooling systems.

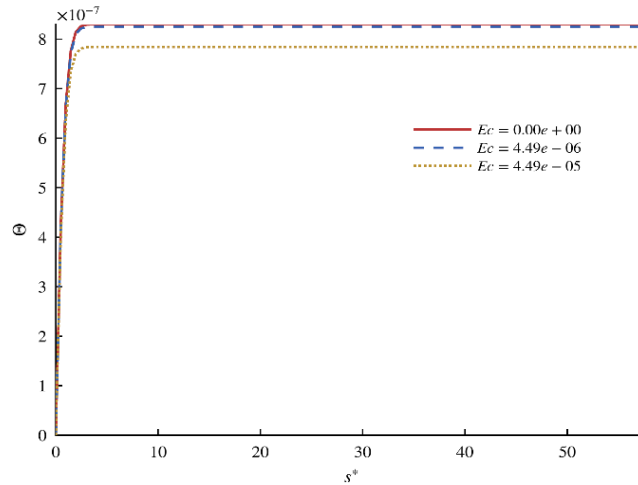


Figure 7. Effect of the Eckert number on the dimensionless temperature Θ for the Pb-17Li coolant

4.6. Effect of peclet number

This section explores the influence of the Peclet number (Pe) on the thermal field and highlights the tradeoff between convective heat transfer and diffusion over the length of the channel. This number controls the ratio of tangential convection to diffusion in the energy equation [20].

Figure 8 shows the negligible impact of the Peclet number on the dimensionless temperature distribution concerning the tangential direction in the considered range for Pb-17Li+AlN nanofluid [20], [22], [24]. For all values, the temperature remains almost constant along the channel. There is also no appreciable alteration in the thermal slope as Pe increases, which shows that convective heat transfer prevails and will suppress thermal diffusion effect. This behaviour is attributed to the increasing dominance of convective heat transport over thermal diffusion, which confines the thermal boundary layer closer to the heated wall. The tiny numerical value pertaining to temperature suggests that the thermal response of the system is stable at the current operating regime and does not produce increasing temperature with respect to the stream path. A corresponding reduction in thermal penetration toward the channel core was also observed as the Peclet number increased, indicating that heat transfer became increasingly dominated by convection.

These findings suggest that operating at higher Peclet numbers improves convective heat transport efficiency while reducing thermal diffusion into the bulk flow, which is advantageous for high-performance fusion reactor cooling systems.

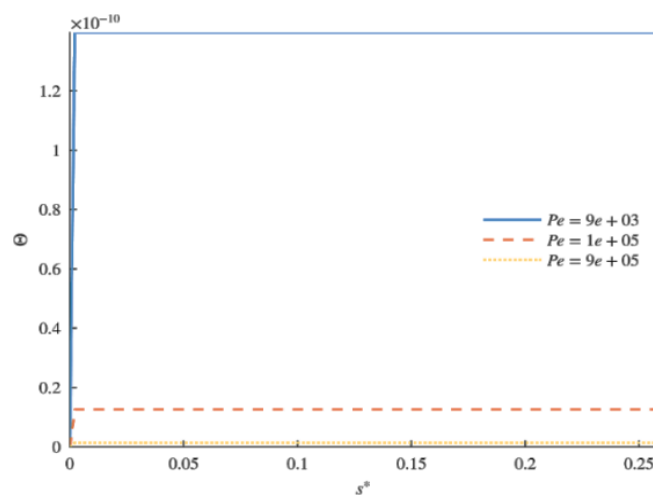


Figure 8. Effect of the Peclet number on the dimensionless temperature θ along the streamwise direction at $r = r_{mid}$ for the Pb-17Li+AlN nanofluid

4.7. Effect of volumetric heat generation number

This section considers the influence of the volumetric heat generation number (Ω_{vol}) on the development of the temperature field in the flow direction, and on the importance of internal heat addition as a source term in the energy equation [20].

Figure 9 demonstrates the influence of volumetric heat generation mechanism on temperature at a given location along the flow direction for a Pb-17Li+AlN nanofluid. Note that increasing the volumetric heat generation coefficient results in a temperature rise uniformly throughout the channel as would be expected from the role of volumetric heat generation energy in the thermal energy balance since this increase in temperature is governed by the cumulative effect of this volumetric energy source which increases the thermal field along the channel as opposed to convection and viscous heating [20], [22], [24].

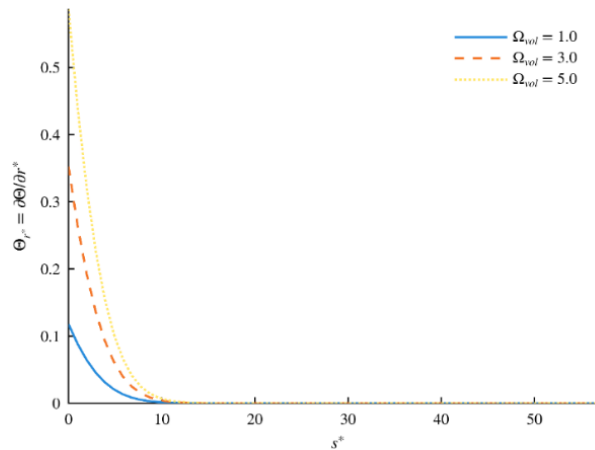


Figure 9. Effect of the volumetric heat generation number on the dimensionless temperature Θ along the streamwise direction at $r = r_{mid}$ for the Pb-17Li+AlN nanofluid

4.8. Practical applications of integrated and reconfigurable monitoring

The proposed finite-difference framework can be adapted for IoT-enabled monitoring, digital-twin platforms, and FPGA/VLSI acceleration of reactor cooling systems. By combining sensor data with the numerical model, thermo-hydraulic states can be estimated in real time, supporting low-latency monitoring and predictive control of advanced cooling systems [25]–[28].

5. CONCLUSION

A unified finite-difference computational framework has been developed to investigate MHD flow, pressure evolution, and heat transfer in a curved porous cooling channel representative of fusion reactor blanket systems. The proposed formulation simultaneously incorporates channel curvature, Darcy–Brinkman–Forchheimer porous resistance, Lorentz-force damping, viscous dissipation, convective heat transfer, and volumetric heat generation within a single MATLAB-based numerical model. In addition, the thermo-hydraulic behaviour of four candidate fusion coolants (water, helium, Pb–17Li, and Pb–17Li+AlN nanofluid) was evaluated under identical operating conditions.

The numerical results demonstrate that channel curvature generates secondary-flow effects and modifies the velocity distribution, whereas decreasing permeability and increasing nonlinear porous resistance substantially increase the hydraulic pressure losses. For electrically conductive coolants, stronger magnetic interaction suppresses fluid motion through Lorentz-force damping, improving flow stability while increasing the pumping requirement. Thermal analyses further indicate that, within the investigated operating range, the influence of viscous dissipation remains limited because convection and Joule heating dominate the energy transport, whereas volumetric heat generation produces the most significant increase in coolant temperature. Among the investigated coolants, the Pb–17Li+AlN nanofluid exhibits the best overall thermal performance, although this improvement is accompanied by increased hydraulic resistance.

The principal contribution of this work lies in integrating channel curvature, porous-medium transport, MHD effects, pressure evolution, and heat transfer into a unified computational framework that enables consistent thermo-hydraulic comparison of multiple fusion-relevant coolants. The developed

numerical methodology also provides a physics-based computational core that is compatible with embedded monitoring architectures, digital-twin platforms, and future FPGA/VLSI acceleration for real-time reactor cooling assessment.

The present study is limited to steady, two-dimensional, laminar flow under the quasi-static MHD approximation with homogeneous porous properties. Future work will extend the model to three-dimensional configurations, variable thermophysical properties, turbulence effects, and experimental validation, while investigating hardware-accelerated implementations for intelligent IoT-enabled monitoring and predictive control of advanced fusion reactor cooling systems.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Hassan Mohammad Hassan	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	✓
Liqaa Zeki Hummady		✓				✓		✓	✓	✓	✓	✓		

C : **C**onceptualization

M : **M**ethodology

So : **S**oftware

Va : **V**alidation

Fo : **F**ormal analysis

I : **I**nterpretation

R : **R**esources

D : **D**ata Curation

O : Writing - **O**riginal Draft

E : Writing - Review & **E**ditng

Vi : **V**isualization

Su : **S**upervision

P : **P**roject administration

Fu : **F**unding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

- [1] G. Federici *et al.*, "Plasma-material interactions in current tokamaks and their implications for next step fusion reactors," *Nuclear Fusion*, vol. 41, no. 12, pp. 1967–2137, 2001, doi: 10.1088/0029-5515/41/12/218.
- [2] H. Zohm *et al.*, "On the physics guidelines for a tokamak DEMO," *Nuclear Fusion*, vol. 53, no. 7, p. 073019, Jul. 2013, doi: 10.1088/0029-5515/53/7/073019.
- [3] C. Mistrangelo, L. Bühler, S. Smolentsev, V. Klüber, I. Maione, and J. Aubert, "MHD flow in liquid metal blankets: Major design issues, MHD guidelines and numerical analysis," *Fusion Engineering and Design*, vol. 173, Art. no. 112795, 2021, doi: 10.1016/j.fusengdes.2021.112795.
- [4] S. Smolentsev, R. Moreau, L. Bühler, and C. Mistrangelo, "MHD thermo-fluid issues of liquid-metal blankets: Phenomena and advances," *Fusion Engineering and Design*, vol. 85, no. 7–9, pp. 1196–1205, Dec. 2010, doi: 10.1016/j.fusengdes.2010.02.038.
- [5] S. Smolentsev, "Physical background, computations and practical issues of the magnetohydrodynamic pressure drop in a fusion liquid metal blanket," *Fluids*, vol. 6, no. 3, p. 110, Mar. 2021, doi: 10.3390/fluids6030110.
- [6] W. R. Dean, "XVI. Note on the motion of fluid in a curved pipe," *The London, Edinburgh, and Dublin Philosophical Magazine and Journal of Science*, vol. 4, no. 20, pp. 208–223, Jul. 1927, doi: 10.1080/14786440708564324.
- [7] S. A. Berger, L. Talbot, and L. S. Yao, "Flow in Curved Pipes," *Annual Review of Fluid Mechanics*, vol. 15, no. 1, pp. 461–512, Jan. 1983, doi: 10.1146/annurev.fl.15.010183.002333.
- [8] D. A. Nield and A. Bejan, "Convection in Porous Media," 1992, doi: 10.1007/978-1-4757-2175-1.
- [9] K. Vafai, Ed., *Handbook of Porous Media*. CRC Press, 2015, doi: 10.1201/b18614.
- [10] H. Darcy, "Les fontaines publiques de la ville de Dijon, Paris, France: Dalmont," 1856, [Online] Available: <https://bm.dijon.fr/doc/SYRACUSE/727711>.
- [11] H. C. Brinkman, "A calculation of the viscous force exerted by a flowing fluid on a dense swarm of particles," *Applied Scientific Research*, vol. 1, no. 1, pp. 27–34, 1949, doi: 10.1007/BF02120313.
- [12] W. Ehlers, "Darcy, Forchheimer, Brinkman and Richards: classical hydromechanical equations and their significance in the light of the TPM," *Archive of Applied Mechanics*, vol. 92, pp. 619–639, 2022, doi: 10.1007/s00419-020-01802-3.
- [13] P. A. Davidson, *Introduction to Magnetohydrodynamics*, Cambridge University Press, 2016, doi: 10.1017/9781316672853.

- [14] R. Moreau, *Magnetohydrodynamics*, vol. 3. Dordrecht: Springer Netherlands: Kluwer Academic Publishers, 1990, doi: 10.1007/978-94-015-7883-7.
- [15] H. K. Moffatt, "On the suppression of turbulence by a uniform magnetic field," *Journal of Fluid Mechanics*, vol. 28, no. 3, pp. 571–592, May 1967, doi: 10.1017/S0022112067002307.
- [16] G. K. Batchelor, *An Introduction to Fluid Dynamics*. Cambridge University Press, 2000, doi: 10.1017/cbo9780511800955.
- [17] F. M. White, "Viscous Fluid Flow, 3rd ed.," New York, NY, USA: McGraw-Hill, 2006.
- [18] P. K. Kundu, I. M. Cohen and D. R. Dowling, "Fluid Mechanics," Elsevier, 6th ed. Oxford, U.K.: Academic Press, 2016, doi: 10.1016/c2012-0-00611-4.
- [19] S. V. Patankar, *Numerical Heat Transfer and Fluid Flow*, Washington, DC, USA: Hemisphere Publishing Corporation, 1980.
- [20] M. Mobedi and G. G. Ilis, *Fundamentals of Heat Transfer: An Interdisciplinary Analytical Approach*. Singapore: Springer, 2023, doi: 10.1007/978-981-99-0957-5.
- [21] D. A. Nield and C. T. Simmons, "A Brief Introduction to Convection in Porous Media," *Transport in Porous Media*, vol. 130, no. 1, pp. 237–250, 2019, doi: 10.1007/s11242-018-1163-6.
- [22] Z. Guo, "A review on heat transfer enhancement with nanofluids," *Journal of Enhanced Heat Transfer*, vol. 27, no. 1, pp. 1–70, 2020, doi: 10.1615/JEnhHeatTransf.2019031575.
- [23] F. Barbier, P. Deloffre, and A. Terlain, "Compatibility of materials for fusion reactors with Pb-17Li," *Journal of Nuclear Materials*, vol. 307–311, no. 2 SUPPL., pp. 1351–1354, 2002, doi: 10.1016/S0022-3115(02)00987-X.
- [24] Q. Tao, F. Zhong, Y. Deng, Y. Wang, and C. Su, "A Review of Nanofluids as Coolants for Thermal Management Systems in Fuel Cell Vehicles," *Nanomaterials*, vol. 13, no. 21, 2023, doi: 10.3390/nano13212861.
- [25] L. D. Xu, W. He, and S. Li, "Internet of things in industries: A survey," *IEEE Transactions on Industrial Informatics*, vol. 10, no. 4, pp. 2233–2243, 2014, doi: 10.1109/TII.2014.2300753.
- [26] R. Minerva, G. M. Lee, and N. Crespi, "Digital Twin in the IoT Context: A Survey on Technical Features, Scenarios, and Architectural Models," in *Proceedings of the IEEE*, vol. 108, no. 10, pp. 1785–1824, Oct. 2020, doi: 10.1109/JPROC.2020.2998530.
- [27] J. P. Durbano, F. E. Ortiz, J. R. Humphrey, P. F. Curt, and D. W. Prather, "FPGA-based acceleration of the 3D finite-difference time-domain method," in *Proceedings - 12th Annual IEEE Symposium on Field-Programmable Custom Computing Machines, FCCM 2004*, 2004, pp. 156–163, doi: 10.1109/FCCM.2004.37.
- [28] F. Pardo, P. López, D. Cabello, and M. Balsi, "FPGA computation of the 3D heat equation," *Computational Geosciences*, vol. 14, no. 4, pp. 649–664, Sep. 2010, doi: 10.1007/s10596-009-9177-3.

BIOGRAPHIES OF AUTHORS



Hassan Mohammad Hassan    received his B.Sc. degree in Mathematics and Computer Applications from the Department of Mathematics and Computer Applications, Al-Nahrain University, Baghdad, Iraq. He is currently a postgraduate researcher in the Department of Mathematics, University of Baghdad, Baghdad, Iraq. His research interests include applied mathematics, fluid mechanics, magnetohydrodynamics, porous-media flow, numerical simulation, and heat-transfer modeling for engineering and reactor-cooling applications. In the present study, he contributed to the mathematical formulation, MATLAB R2025b software implementation, numerical simulation, validation, visualization, analysis of results, and preparation of the original manuscript. He can be contacted at email: hasan.hasan2303@sc.uobaghdad.edu.iq.



Liqaa Zeki Hummady    is a faculty member in the Department of Mathematics, College of Science, University of Baghdad, Iraq. She received her Ph.D. in Applied Mathematics and has extensive experience in teaching and research in fluid mechanics, heat and mass transfer, porous media, non-Newtonian fluids, mathematical modeling, and numerical analysis. She is committed to promoting scientific research and higher education through teaching, supervision, and academic service. She supervised the present research and contributed to the conceptualization of the study, methodology development, scientific supervision, formal analysis, interpretation of results, and manuscript review and editing. She can be contacted at email: liqa.hummady@sc.uobaghdad.edu.iq.