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Numerical Investigation of Flow Dynamics and Heat Transfer in a Baffled Geometry Using Al_2O_3–Water Nanofluid

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Abstract

A detailed numerical investigation is carried out to explore the thermal and hydrodynamic behaviour of nanofluid flow through a circular pipe with multiple internal baffles considering axisymmetric geometry. The objective is to understand the mechanisms behind convective heat transfer enhancement using nanofluids in thermally demanding systems. Aluminium oxide (Al_2O_3) nanoparticles suspended in water are used as the working fluid, with varying volume concentrations to assess their impact. The pipe features uniformly spaced baffles to promote secondary flows and thermal mixing. Boundary conditions include a fully developed velocity profile and constant fluid temperature at the inlet, while the pipe wall is maintained at a constant elevated temperature. The simulations are conducted using the Control Volume Method with the SIMPLER algorithm and a power-law scheme. Results show that the presence of nanoparticles significantly improves heat transfer due to enhanced thermal conductivity. However, this benefit is accompanied by increased flow resistance, highlighting a performance trade-off in nanofluid applications.

Keywords: Reattachment Length, Reynolds Number, Nusselt Number, Al_2O_3-Water Nano Fluid and Nano Fluid Volume Fraction

1. Introduction

The study of flow separation and reattachment in baffled geometries has garnered significant attention due to its relevance in enhancing heat transfer in various engineering systems. Baffles are commonly integrated into channels to disturb the flow, promoting turbulence and increasing the heat transfer coefficient. However, the presence of baffles also leads to flow separation and the formation of recirculation zones, which influence the thermal and hydraulic performance. The reattachment length, defined as the distance from the baffle to the point where the flow reattaches to the wall, is a crucial parameter in characterizing these flow behaviors.

Early numerical and experimental investigations have provided insight into the hydrodynamics of flow over backward-facing steps, a classic model for studying separation and reattachment phenomena. Research on heat transfer enhancement techniques has evolved significantly over the past few decades, with particular emphasis on numerical methods and nanofluid applications. One of the foundational works in computational heat transfer was presented by Patankar (1980), who developed a robust numerical framework using the finite volume method. This work laid the groundwork for solving complex convective heat transfer problems with accuracy and stability. The behavior of separated flows, such as those occurring downstream of a backward-facing step, was investigated both experimentally and theoretically by Armaly et al. (1983). Their findings have served as benchmark data for validating numerical simulations, especially in recirculating flow regimes. The advent of nanofluids, initiated by Choi (1995), marked a pivotal point in enhancing the thermal conductivity of base fluids through the dispersion of nanoparticles. This concept was further explored by Xuan and Li (2000), who demonstrated that nanofluids not only improve thermal transport properties but also significantly enhance convective heat transfer performance under specific flow conditions.

Khanafer et al. (2003) conducted a numerical investigation of buoyancy-driven convection in enclosures filled with nanofluids. Their study confirmed that incorporating nanoparticles, particularly Al2O3, enhances heat transfer due to improved thermal conductivity and modified flow structures. To further quantify the thermal conductivity enhancement of Al2O3-water nanofluids, Chon et al. (2005) proposed an empirical correlation considering the influence of both particle size and fluid temperature. Extending the application of nanofluids to complex cavity geometries, Tiwari and Das (2007) analyzed lid-driven cavities, revealing notable heat transfer augmentation due to the interaction between lid motion and nanoparticle dispersion. In parallel, Lee et al. (2008) examined the effective thermal conductivities and viscosities of low-concentration Al2O3-water nanofluids, providing vital property data for practical use. The dispersion stability and its effect on thermal performance were addressed by Zhu et al. (2009), who showed that better dispersion leads to higher thermal conductivity and more efficient heat removal. Meanwhile, Bhattacharya et al. (2009) focused on microchannel heat sinks, highlighting the combined impact of conjugate heat transfer and nanofluid flow in compact geometries. In more recent developments, Moghadassi et al. (2015) compared the heat transfer performance of single (Al2O3) and hybrid (Al2O3–Cu) nanofluids under forced convection, indicating superior enhancement for hybrid formulations due to synergistic effects. Similarly, Boukerma and Kadja (2017) explored various water-ethylene glycol mixtures with both Al2O3 and CuO nanoparticles, emphasizing the importance of base fluid selection and nanoparticle type on thermal performance.

Khudheyer et al. (2018) evaluated the forced convective heat transfer over finned tubes using Al2O3-water nanofluids, revealing substantial improvements in heat dissipation, especially with circular fin geometries. Most recently, Klazly and Bognar (2022) revisited the backward-facing step configuration, this time at the microscale using nanofluids. Their study demonstrated that scale reduction, coupled with nanoparticle-enhanced fluids, results in considerable improvement in convective heat transfer rates.

2. Mathematical Description

Governing Equations:

The study focuses on a cylindrical pipe configuration that includes a centrally placed cylindrical rod equipped with baffles, as illustrated in the accompanying figure 1. The pipe has an inner diameter of 22 mm and extends over a length of 200 mm. The working fluid is a nanofluid, modeled as Newtonian, incompressible, and exhibiting laminar flow characteristics. Nanoparticles suspended in the base fluid are assumed to be uniformly distributed, identical in size and shape, and in thermal equilibrium with the surrounding fluid. Due to their small size, slip velocity between the solid and liquid phases is considered negligible. The wall temperature of both the pipe and the internal baffled rod is maintained at 350 K, while the inlet fluid enters at a temperature of 300 K.

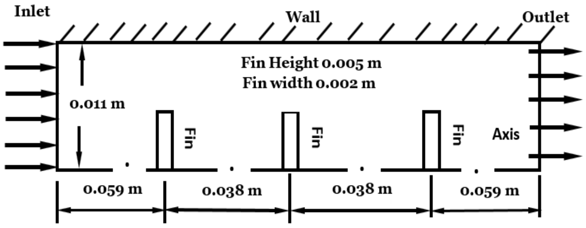

Fig.1. The Physical Geometry of the Problem described

The governing equations in cylindrical coordinate system are

Incompressible continuity equation

$$\frac{1}{r}\frac{\partial(ru_r)}{\partial r}+\frac{1}{r}\frac{\partial u_\theta}{\partial \theta}+\frac{\partial u_z}{\partial z}=0$$

Momentum equation

r-component-

$$\rho_{nf}\left(\frac{\partial u_r}{\partial t}+u_r\frac{\partial u_r}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_r}{\partial \theta}-\frac{{u_\theta}^2}{r}+u_z\frac{\partial u_r}{\partial z}\right) = -\frac{\partial P}{\partial r}+\rho_{nf}g_r + \mu_{nf}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_r}{\partial r}\right)-\frac{u_r}{r^2}+\frac{1}{r^2}\frac{\partial^2 u_r}{\partial \theta^2} -\frac{2}{r^2}\frac{\partial u_\theta}{\partial \theta}+\frac{\partial^2 u_r}{\partial z^2}\right]$$

θ-component

$$\begin{aligned}\rho_{nf}\left(\frac{\partial u_\theta}{\partial t}+u_r\frac{\partial u_\theta}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_\theta}{\partial \theta}+\frac{u_r u_\theta}{r}+u_z\frac{\partial u_\theta}{\partial z}\right)\\ &= -\frac{1}{r}\frac{\partial P}{\partial \theta}+\rho_{nf}g_\theta\\ &+\mu_{nf}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_\theta}{\partial r}\right)-\frac{u_\theta}{r^2}+\frac{1}{r^2}\frac{\partial^2 u_\theta}{\partial \theta^2}\right.\\ &\left.+\frac{2}{r^2}\frac{\partial u_r}{\partial \theta}+\frac{\partial^2 u_\theta}{\partial z^2}\right]\end{aligned}$$

z-component

$$\begin{aligned}\rho_{nf}\left(\frac{\partial u_z}{\partial t}+u_r\frac{\partial u_z}{\partial r}+\frac{u_\theta}{r}\frac{\partial u_z}{\partial \theta}+u_z\frac{\partial u_z}{\partial z}\right)\\ &= -\frac{\partial P}{\partial z}+\rho_{nf}g_z\\ &+\mu_{nf}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial u_z}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 u_z}{\partial \theta^2}\right.\\ &\left.+\frac{\partial^2 u_z}{\partial z^2}\right]\end{aligned}$$

Energy equation

$$\begin{aligned}(\rho C_p)_{nf}\left(\frac{\partial T}{\partial t}+u_r\frac{\partial T}{\partial r}+\frac{u_\theta}{r}\frac{\partial T}{\partial \theta}+u_z\frac{\partial T}{\partial z}\right)\\ &= k_{nf}\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)+\frac{1}{r^2}\frac{\partial^2 T}{\partial \theta^2}+\frac{\partial^2 T}{\partial z^2}\right]\\ &+S\end{aligned}$$

Assumptions:

The problem is treated as axisymmetric, implying that variations in the circumferential (θ) direction are absent. Additionally, the source term in the energy equation is set to zero (S = 0), indicating the absence of internal heat generation within the fluid.

Dynamic viscosity can be estimated by Brinkman model:

$$\mu_{nf}=\frac{\mu_f}{(1-\emptyset)^{2.5}}$$

The effective density and heat capacity of the nanofluid at reference temperature (Tin=300K) can be estimated by:

$$\rho_{nf}=(1-\emptyset)\rho_f+\emptyset\rho_s$$

$$(\rho C_p)_{nf}=(1-\emptyset)\left(\rho C_p\right)_f+\emptyset(\rho C_p)_s$$

Maxwell-Garnett's model can be used to calculate the effective thermal conductivity of a spherical particle suspension.

$$\frac{k_{nf}}{k_f}=\frac{k_s+2k_f-2\emptyset(k_f-k_s)}{k_s+2k_f+\emptyset(k_f-k_s)}$$

BOUNDARY CONDITIONS:

At the inlet:

$u_z=u_{in}=constant, u_r=u_\theta=0$,
$T=T_{in}=constant$

At the pipe wall:

No-slip boundary conditions, $u_r=u_\theta=u_z=0$,
$T=T_{wall}=constant$

Axis:

Axi-symmetric boundary conditions: $\frac{\partial(\alpha)}{\partial r}=0.$ Where, $\alpha=Any\ variable.$

At the insertion of baffle:

$u_r=u_\theta=u_z=0$, $T=T_{wall}=constant$

$T_{in}<T_{wall}$

At outlet boundary:

Atmospheric pressure boundary condition, or, $p_{gauge}=0$

3. Results And Discussions

ISOTHERMAL LINES AROUND MIDDLE BAFFLE FOR DIFFERENT NANOPARTICLE VOLUME FRACTION

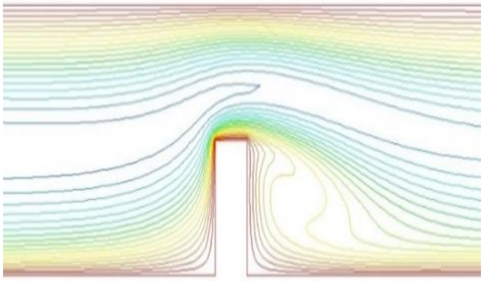

Fig.2(a): Isotherm for ϕ=0%

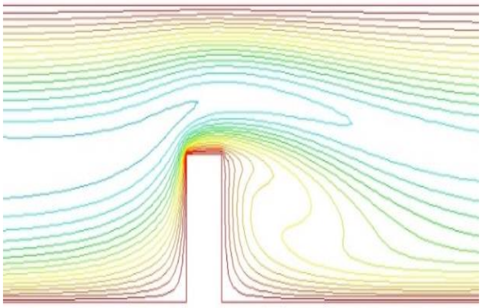

Fig.2(b): Isotherm for ϕ=5%

Figures 2(a) and 2(b) display the temperature isotherms corresponding to nanoparticle volume fractions of 0% and 5%. A clear comparison of these results shows noticeable changes in the contour distribution as the concentration of nanoparticles increases. The observed modifications in the isotherm patterns indicate stronger thermal activity within the fluid domain, pointing to a significant enhancement in overall heat transfer performance. The distortion and redistribution of isotherms with higher particle concentration suggest more efficient thermal diffusion, which is directly related to the improved thermal conductivity of the nanofluid. These findings emphasize the effectiveness of nanofluids in improving thermal system performance and underline their potential for use in advanced thermal management applications.

VELOCITY VECTORS AROUND MIDDLE BAFFLE FOR DIFFERENT NANOPARTICLE VOLUME FRACTION

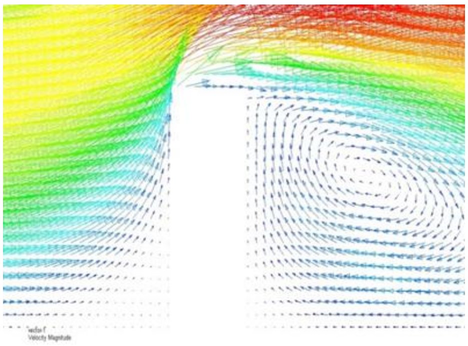

Fig. 3(a): Velocity Vector when ϕ = 0%

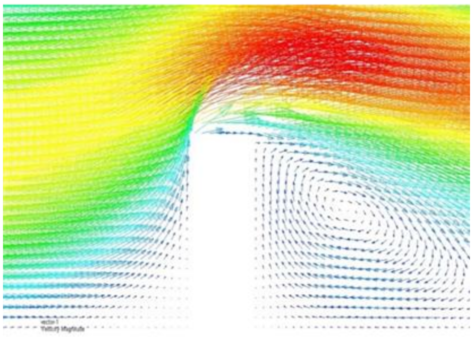

Fig. 3(b): Velocity Vector when ϕ = 5%

Figures 3(a) and 3(b) present the velocity vector distributions for nanoparticle volume fractions of 0% and 5%, respectively. A comparative analysis of these results indicates clear modifications in flow characteristics with the addition of nanoparticles. The velocity fields show variations in pressure distribution around the fins, highlighting that nanoparticle incorporation influences the hydrodynamic response of the fluid. These changes arise primarily from the increased viscosity and thermal conductivity associated with nanofluids.

Both figures also reveal the formation of recirculating regions, particularly upstream of the baffle along the main flow direction. At 5% volume fraction, these recirculation zones become more distinct, suggesting that higher nanoparticle concentrations enhance vortex intensity and local fluid motion. Such intensified circulation improves convective heat transfer by disturbing thermal boundary layers and promoting fluid mixing.

This behaviour not only enhances temperature uniformity within the domain but also reflects the superior heat storage potential of nanofluids. The improved capacity can be linked to their higher specific heat and responsiveness to thermal fluctuations. Overall, the findings emphasize the hydrodynamic and thermal benefits of using nanoparticle-enriched fluids, providing valuable guidance for optimizing heat transfer in finned and baffled geometries.

NUSSELT NUMBER VARIATION WITH DIFFERENT NANOPARTICLE VOLUME FRACTION

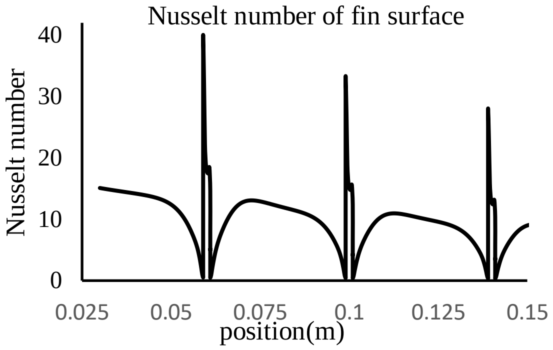

Fig. 4(a): when ϕ = 0%

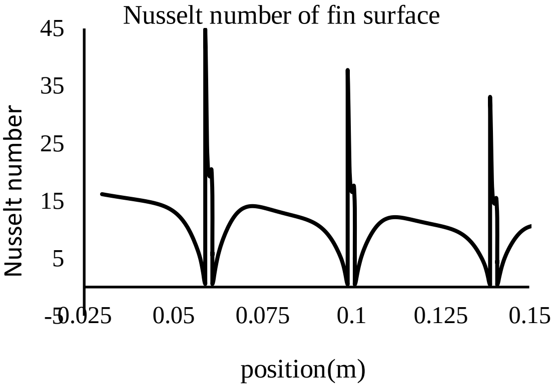

Fig. 4(b): when ϕ = 5%

The Nusselt number (Nu) characterizes the convective heat transfer effectiveness of a surface. It represents the ratio of convective to conductive heat transfer across a boundary layer. In the context of a fin surface immersed in a nanofluid, the Nusselt number describes how effectively heat is transferred from the fin to the surrounding fluid.

The relationship between the Nusselt number of a fin surface and nanofluid volume concentration is influenced by various factors, including nanoparticle properties, fluid flow conditions, and fin geometry. Similar to the overall heat transfer rate, low concentrations of nanoparticles in the nanofluid can enhance the Nusselt number compared to the base fluid. This enhancement is primarily due to the improved thermal conductivity of the nanofluid, which promotes more efficient heat transfer across the boundary layer. In the figures 4(a) and 4(b) Nusselt number for different volume fractions of 0 and 5 percent have been presented. It's observed that Nusselt Number slowly increased when nanofluid volume concentration is increased. It's also observed that Nusselt number gradually decreased for next two baffles.

VARIATION IN REATTACHMENT LENGTH AS A FUNCTION OF NANOPARTICLE VOLUME FRACTION AND REYNOLDS NUMBER

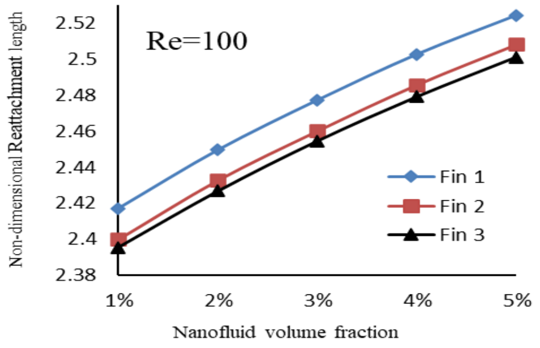

Fig. 5(a)

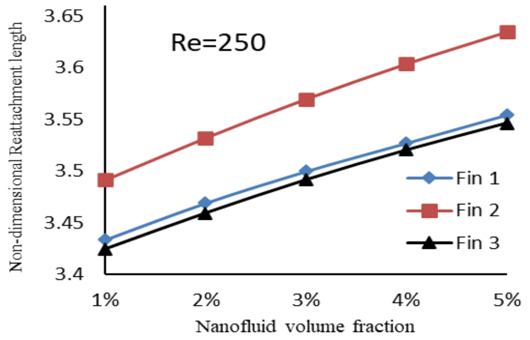

Fig. 5(b)

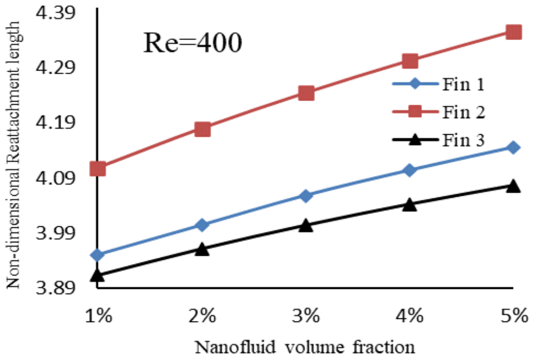

Fig. 5(c)

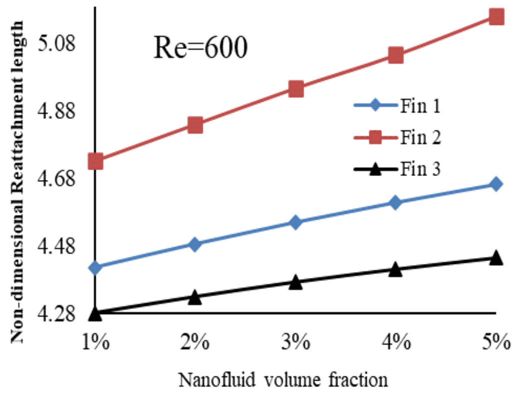

Fig. 5(d)

Figures 5(a) through 5(d) illustrate the variation in recirculation bubble strength as a function of nanoparticle volume fraction and Reynolds number, respectively. These visualizations clearly demonstrate that, for a fixed baffle geometry, the strength of the recirculation bubble exhibits a noticeable increase with both the rise in nanofluid volume fraction and the Reynolds number. This trend can be attributed to the enhanced adverse pressure gradient that develops due to both parameters. As the volume fraction of nanoparticles in the base fluid increases, the fluid's thermal and momentum diffusivities are altered, leading to intensified vortex formation and consequently a more pronounced recirculation zone. Similarly, an increase in Reynolds number signifies a higher inertial force relative to viscous effects, further promoting flow separation and the enlargement of the recirculation region in terms of both length and width. Quantitatively, the average increase in recirculation bubble strength due to nanofluid volume fraction enhancement is approximately 1%. In contrast, the corresponding increase attributed to a rise in Reynolds number is about 0.7% on average. These results highlight the sensitivity of flow separation characteristics to both thermophysical properties of the working fluid and flow dynamics, which are crucial considerations in the design and optimization of thermal systems incorporating nanofluids and baffle-induced flow modifications.

VARIATION IN REATTACHMENT LENGTH AS A FUNCTION OF REYNOLDS NUMBER AND NANOPARTICLE VOLUME FRACTION

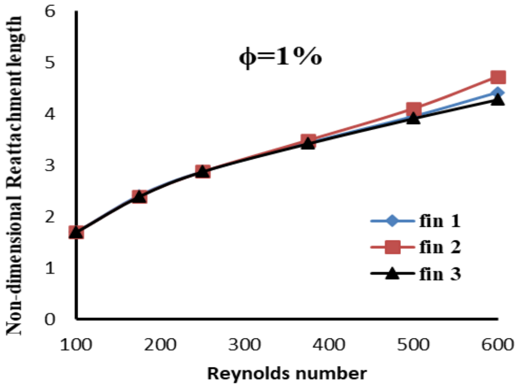

Fig. 6(a)

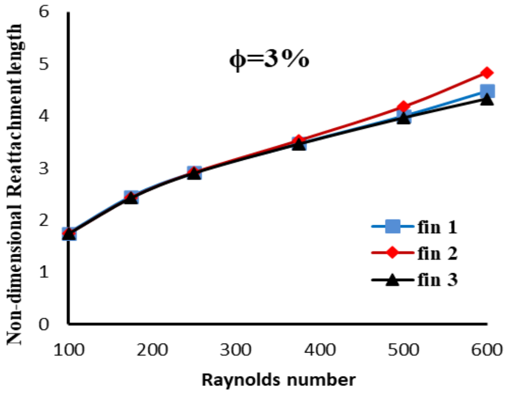

Fig. 6(b)

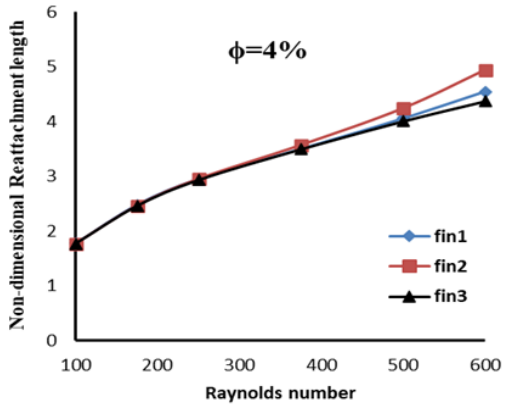

Fig. 6(c)

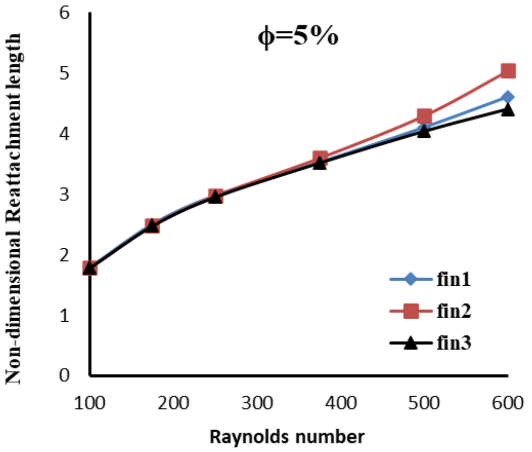

Fig. 6(d)

Figures 6(a) through 6(d) depict the variation of non-dimensional reattachment lengths associated with recirculation bubbles as a function of Reynolds number, under different nanoparticle volume fractions, in cases where fins are axially inserted into the flow domain. These results offer valuable insights into the complex interplay between fluid dynamics and thermal transport in nanofluid systems featuring internal obstructions. The inclusion of fins along the pipe axis introduces significant disturbances to the flow field, causing flow separation, promoting enhanced fluid mixing, and substantially modifying the reattachment behavior of the separated flow. The combination of varying nanoparticle concentrations and fin-induced geometric perturbations contributes to a highly intricate flow and heat transfer regime, deviating considerably from that of smooth pipe flow. From the observed trends, it is evident that the reattachment length of the recirculation bubbles consistently increases with rising Reynolds number across all tested volume fractions of the nanofluid. This can be attributed to the strengthening of inertial forces at higher Reynolds numbers, which extends the distance over which the separated flow reattaches downstream of the fins. Additionally, the presence of nanoparticles alters the thermophysical properties of the base fluid, further influencing the flow structure and thermal boundary layer development. These findings underscore the importance of considering both fluid composition and internal structural modifications when analyzing and designing thermofluidic systems utilizing nanofluids.

4. Conclusion

This study presents a detailed analysis of nanofluid flow through an axisymmetric circular pipe featuring uniformly spaced baffles along its central axis. The influence of baffle placement on the hydrodynamic and thermal behavior of the nanofluid has been systematically investigated. Particular attention is given to the mode of heat transfer and the formation of recirculation regions downstream of the baffles. The extent and intensity—commonly referred to as the length and breadth—of the recirculation bubbles have been quantified, serving as indicators of flow strength and mixing enhancement. The results reveal a distinct and organized pattern in both heat transfer enhancement and vortex formation due to the baffle insertions. This behavior is especially relevant for similar configurations involving nanofluids or baffle-assisted heat transfer applications.

These findings are crucial for the optimal design and application of nanofluid-based cooling systems, where thermal performance and pumping power requirements must be balanced. The insights from this work provide valuable guidance for the thermal management of compact heat exchangers, electronic cooling systems, and other advanced thermal devices employing nanofluid technology.

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