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Theoretical Estimation of the Reattachment Length of the Recirculation Bubble and Conjugate Heat Transfer In a 2-D Geometry Having Multiple Baffles Using Combination of CuO-Water Nano-Fluid

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ABSTRACT

A numerical investigation of nanofluid flow and heat transmission through a circular pipe has been carried out. The nanofluid considered is a CuO-water mixture with varying volume fractions. The inlet flow has been assumed to be uniform at a constant temperature. In addition, the wall temperature is constant. The numerical methodology employed is S. V. Patankar's Control Volume Formulation, which employs the SIMPLER algorithm and a power law scheme. The results reveal a significant increase in overall heat transfer rate as the nanoparticle volume fraction increases, at the expense of pressure decrease.

KEYWORDS: Reattachment length, Reynolds Number, Heat transfer, CuO-water nano fluid and, Volume fraction

NOMENCLATURE:

List of symbols

C_p	Specific Heat at Constant Pressure(J/Kg-K)
h	Heat Transfer Coefficient (W/K-m^2)
K	Thermal conductivity (W/m-K)
Nu	Nusselt Number
P	Pressure(N/m^2)
Re	Reynolds Number
T_w	Temperature at wall(K)

Greek Symbols:

Β	ratio of nanolayer thickness(dimensionless)
Θ	Dimensionless Temperature(dimensionless)
Μ	Coefficient of viscosity (N-s/m^2)
ρ_{nf}	Density of nanofluid (Kg/m^3)
ρ_s	Density of nanoparticles (Kg/ m^3)
Φ	Particle volume fraction of nanofluid (%)

Subscripts:

in	Inlet conditions
nf	Nanofluid
s	Nanoparticles
w	Water

1.INTRODUCTION

In the study of fluid dynamics and heat transfer, the analysis of flow behavior and thermal performance in geometries with obstacles or baffles is a topic of significant interest. Such configurations are commonly encountered in heat exchangers, cooling systems, and energy devices where enhanced heat transfer is essential. Among these, the interaction between fluid flow and thermal properties in the presence of multiple baffles presents unique challenges, especially when nano-fluids are employed.

This paper focuses on the theoretical estimation of the reattachment length of the recirculation bubble and the conjugate heat transfer in a two-dimensional geometry with multiple baffles. The inclusion of baffles induces flow separation and recirculation zones, significantly affecting the heat transfer rates and flow resistance. The reattachment length, defined as the distance from the separation point to the point where the flow reattaches to the surface, is a critical parameter in understanding the flow behavior in such systems.

To further enhance thermal performance, CuO-water nano-fluid is utilized as the working fluid. Nano-fluids, suspensions of nanoparticles in a base fluid, have shown promising capabilities in augmenting heat transfer due to their superior thermal conductivity compared to conventional fluids. The choice of CuO nanoparticles stems from their high thermal conductivity and stability in aqueous suspensions.

The combination of nano-fluid properties with the complex flow patterns induced by multiple baffles creates a dynamic interplay between fluid mechanics and heat transfer. This paper aims to provide a theoretical framework for estimating the reattachment length of the recirculation bubble and analyze the conjugate heat transfer in the presence of CuO-water nano-fluid. The findings have potential applications in optimizing the design of thermal systems and improving energy efficiency in engineering applications.

STRUCTURE OF PAPER

The paper is structured as follows to comprehensively address the theoretical estimation of the reattachment length and conjugate heat transfer in a 2D geometry with multiple baffles using CuO-water nano-fluid: In Section 1, the introduction of the paper is provided along with the structure, important terms, objectives and overall description. In Section 2 we discuss overview of previous studies on flow and heat transfer in baffled geometries & recent advancements in nano-fluid applications for thermal systems. In Section 3 we have the complete information about Governing equations for fluid flow and heat transfer (continuity, momentum, and energy equations), thermophysical properties of CuO-water nano-fluid (density, specific heat, viscosity, thermal conductivity) and Models for evaluating nano-fluid behavior under different flow conditions. Assumptions and approximations used in the study. Section 4 tells us about the methodology and result analysis of the research work. Section 5 tells us about the future scope and concludes the paper with acknowledgement and references.

OBJECTIVES

The primary objective of this paper is to develop a theoretical framework for estimating the reattachment length of the recirculation bubble and analyzing conjugate heat transfer in an axisymmetric geometry with multiple baffles, using a CuO-water nano-fluid. The specific aims are as follows: Investigate the effects of baffle geometry and arrangement on flow separation, recirculation, and reattachment. Evaluate the relationship between baffle-induced flow patterns and reattachment length. Examine the interaction between convective heat transfer in the fluid and conductive heat transfer in the solid baffles. Assess the influence of baffle material properties and nano-fluid characteristics on overall heat transfer performance. To evaluate the impact of CuO-water nano-fluid on thermal performance. Explore the enhancement in heat transfer due to the improved thermal conductivity of CuO-water nano-fluid.

2. RELATED WORK

All liquid coolants, including water, mineral oil, and ethylene glycol, have restricted applicability due to their weak thermal characteristics as compared to solid metals. One of today's most prevalent heat transmission strategies is to mix high conductivity solid particles with a fluid. If millimetre or micrometre sized solid particles are suspended within fluid, it will improve thermal properties, but it will also cause problems such as poor suspension stability, rapid sedimentation, channel clogging, corrosion, pipeline erosion, and a large pressure drop, all of which are extremely detrimental to system performance. Because of these drawbacks, the above technology for heat transfer improvement was not widely adopted. To address these concerns, the use of nanoscale particles was proposed. Choi [1] initially proposed the concept of "nanofluids" in 1995. Nanofluid is a solid-liquid mixture made up of a dilute volume fraction of high conductivity solid nanoparticles and a base fluid. In an experimental study, Eastman et al [2, 3], H. Xie et al [4] demonstrated that thermal conductivity enhancements were obtained by mixing nanoparticles in base fluid, and nanoparticles easily fluidize in the flow due to their small size, overcoming the problems of channel clogging, erosion of channel walls and sedimentation. In an experimental study, Xuan and Li [5] demonstrated convective heat transfer and flow characteristics for a Cu-water nanofluid. They employed a straight tube with a consistent heat flux in both laminar and turbulent flow conditions.

Roy et al. [6] studied the hydrodynamic and thermal properties of water-γAl2O3 nanofluid in a radial laminar flow cooling system. The results show an increase in heat transfer rate for a 10% nanoparticle volume fraction nanofluid, as well as an increase in wall shear stress with increasing particle volume concentration. Liu et al. [7] used a chemical reduction process to create spherical and square-shaped Cu nanoparticles with diameters ranging from 50 to 100 nm. No surfactant was added to the nanofluid. The results showed a 23.4% increase in nanofluid thermal conductivity at a 0.1% volume concentration of Cu nanofluid. Akbarinia and Behzadmehr [8] investigated the numerically completely developed laminar mixed convection of an Al2O3/water nanofluid in horizontal curved tubes, examining the influences of buoyancy force, centrifugal force, and nanoparticle concentration. Chen et al. [9] investigated the rheological behavior of ethylene glycol-based titania nanofluids and measured the shear viscosity of those nanofluids up to 8% on a particle weight basis. They concluded that the shear viscosity of the nanofluids is dependent on particle concentration and temperature.

Abu-Nada et al. [10] investigated the heat transfer enhancement of nanofluids in horizontal concentric annuli with varying volume fractions of Cu, Ag, Al2O3, and TiO2 nanoparticles, using water as the base fluid. Namburuet al. [11] numerically examined the turbulent flow and heat transfer of three different nanofluids including CuO, Al2O3, and SiO2 nanoparticles in an ethylene glycol and water mixture flowing through a circular tube at a constant heat flux. Their predictions about the Nusselt number for nanofluids are compatible with the Gnielinski correlation. Fard et al. [12] used the CFD method to numerically examine the laminar convective heat transfer of nanofluids in a circular tube under constant wall temperature circumstances, comparing a two-phase model to a single-phase model. Laminar forced convection with temperature-dependent thermal conductivity of nanofluids and thermal dispersion was numerically analyzed by Ozerincet al. [13]. The experimental data and the thermal dispersion model are found to be in good agreement. Shedid [14] computationally simulated the thermal behavior of nanofluids traveling through an annular tube using the Spalart-Allmaras (S-A) turbulence model. The Gnielinski correlation for pure water flow is used to validate the suggested model.

3. IMAGE PROCESSING

MATHEMATICAL DESCRIPTION:

Governing equations:

Consider a cylindrical pipe containing a cylindrical rod with baffles (as seen in the image). The pipe has a 22 mm diameter and a length of 200 mm. The nanofluid is assumed to be Newtonian, incompressible, and laminar. The nanoparticles are considered to be uniform in size and shape, and the nanoparticles and base fluid are in thermal equilibrium with one another. Because the particles are small in size, no slip velocity between the phases exists. The temperature of the cylinder wall and the inserted rod with baffle is $T_{wal\,l}$= 350 K, while the incoming fluid temperature is T_{in} = 300 K.

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-

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

θ-component

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

z-component

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

Energy equation

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

Assumptions

We regarded the problem to be axi-symmetric, therefore fluctuations along θ direction are not present. The Source term in the energy equation is zero (S=0), indicating that the fluid does not generate heat energy. 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 boundary

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

At the pipe wall

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

At the insertion baffle

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

$T_{in}<T_{wall}$

At outlet boundary

$$p_{gauge}=0$$

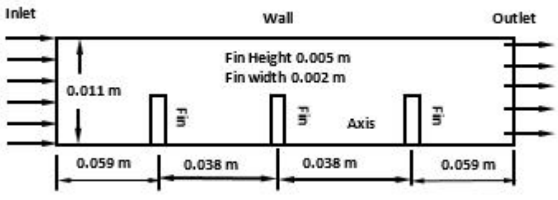
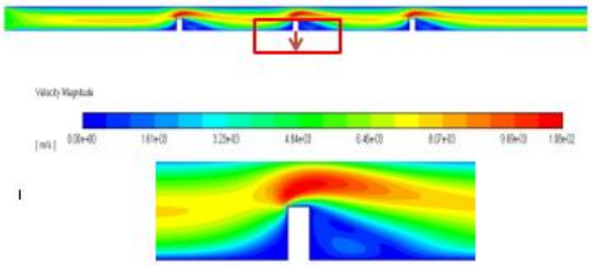


Fig.1, The Physical Geometry of the Problem described



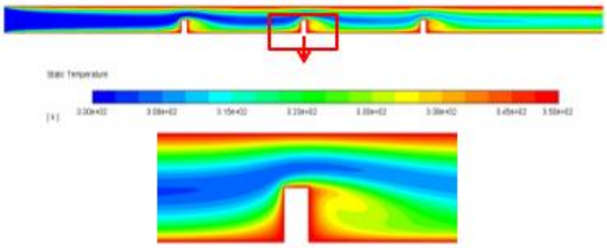


Figure 3: Temperature contour

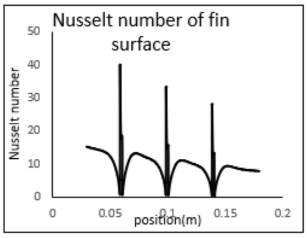


Fig. 4a: when ϕ = 0%

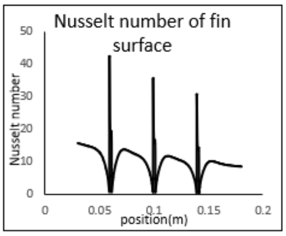


Fig. 4b: when ϕ = 5%

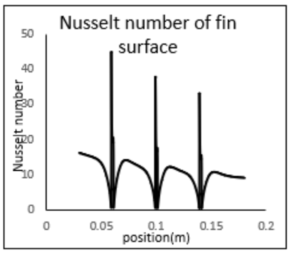


Fig. 4c: when ϕ = 10%

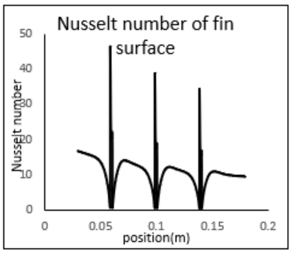


Fig. 4d: when ϕ = 15%

Fig. 4: Nusselt number variation with different nanoparticle volume fraction

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 4a, 4b, 4c and 4d Nusselt number for different volume fractions of 0, 5, 10 and 15 percent have been presented. It's observed that Nusselt Number slowly increased when nanofluid volume concentration is increased. It's also bserved that Nusselt number gradually decreased for next two baffles.

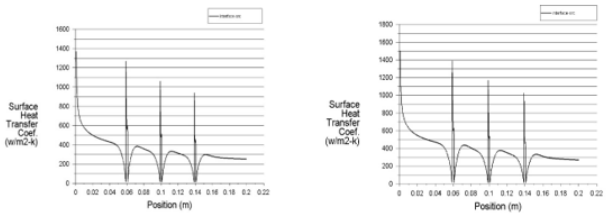


Fig. 5a: when ϕ = 0% Fig. 5b: when ϕ = 5%

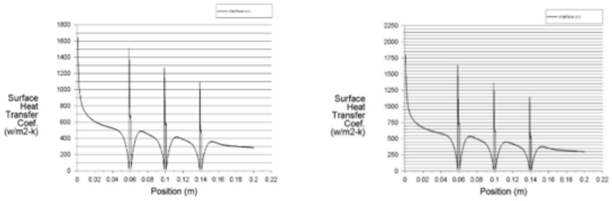


Fig. 5c: when ϕ = 10% Fig. 5d: when ϕ = 15%

Fig. 5: Surface heat transfer coefficient variation of lower surface for different nanoparticle volume fraction

The heat transfer coefficient (h) characterizes the rate of heat transfer between a surface and a fluid. In the context of nanofluids, the heat transfer coefficient describes how efficiently heat is exchanged between the surface and the nanofluid. The relationship between the heat transfer coefficient and nanofluid volume concentration is crucial for understanding the effectiveness of nanofluids in enhancing heat transfer. It's observed that heat transfer coefficient gradually increased in increase in nanofluid volume concentration. Generally, at low nanofluid volume concentrations, the heat transfer coefficient tends to increase compared to the base fluid. This enhancement is primarily due to the increased thermal conductivity of the nanofluid resulting from the presence of nanoparticles. The enhanced thermal conductivity facilitates more efficient heat conduction across the boundary layer, leading to higher convective heat transfer coefficients.

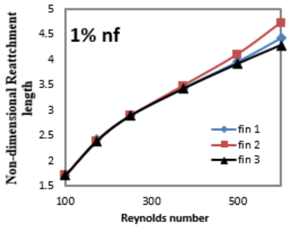


Fig. 6(a)

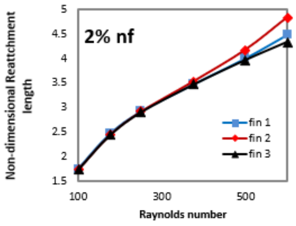


Fig. 6(b)

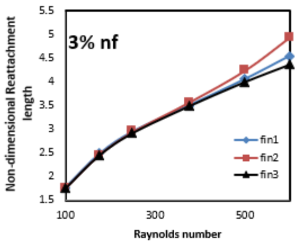


Fig. 6(c)

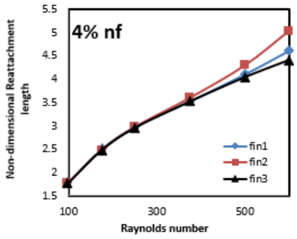


Fig. 6(d)

In the above figures 6(a) to 6(d) the variation of non-dimensional reattachment lengths of the recirculation bubbles and the corresponding Reynolds numbers have been represented when the fins are inserted at the axis with different volume fractions. From the variations we can say that the flow and the heat transfer mode is very complex due to the presence of the fins in addition to the varying volume fraction of the nanoparticles. Fins disturb the flow field, inducing separation, enhancing mixing, and altering reattachment characteristics. Results showing that the reattachment length gradually increases as Reynolds number increased with different nanofluid volume fraction.

In the following figures 7(a) to 7(f) the recirculation bubble strength has been represented with the volume fraction as well as for different Reynolds numbers respectively. From these diagrams it is evident that the recirculation bubble strength increases with volume fraction of the nano fluid as well as with the Reynolds number for same baffle sizes. This is for the reason that the adverse pressure gradient is generated and increased both by the increased in volume fraction of the nano fluid volume fraction and Reynolds number and the recirculation length and breadth increase with the increase in nano fluid volume fraction and Reynolds number. However, the percentage increase of recirculation bubble strength in case of nano fluid volume increase is 1% in average while 0.72 % is the general tendency of the increment of the recirculation bubble strength with respect to the increase of Reynolds number.

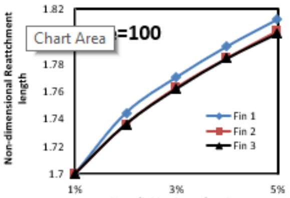


Fig. 7(a)

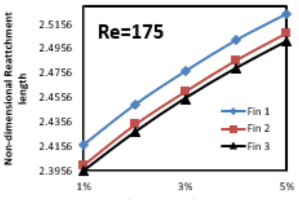


Fig. 7(b)

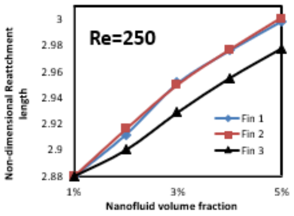


Fig. 7(c)

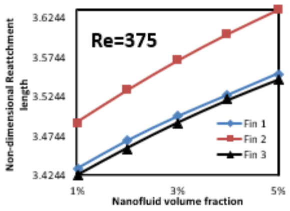


Fig. 7(d)

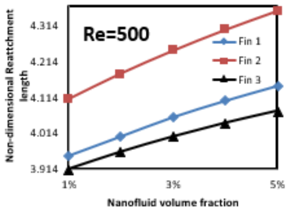


Fig. 7(e)

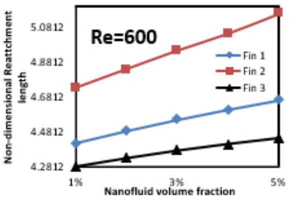


Fig. 7(f)

4. CONCLUSION

An analysis of nano fluid flow through an axi-symmetric circular pipe with insertions of baffles at regular intervals on the axis have been done. The heat transfer mode is analyzed as well as the generation of recirculation bubble length and breadth or simply strength has been captured. There is a very organized pattern of the heat transfer and increased recirculation bubble strength which is important for the same types of flow with the presence of baffles or different nano fluid flows. However further and intensive research and experimentation are needed for this type of complex flows.

Conflict of interest statement

Authors declare that they do not have any conflict of interest.

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