CHAPTER I
INTRODUCTION

1.1 Background

Thermal management and heat exchange efficiency are critical concerns in engineering applications ranging from automotive cooling and HVAC systems to power generation and electronic cooling. As systems become more compact and power-dense, performance increasingly depends on the heat transfer coefficient (h) of the working fluid and the hydrodynamic characteristics of its flow path [1]. Conventional coolants such as water, ethylene glycol, and engine oil are limited by inherently low thermal conductivity, which caps how much heat these systems can dissipate regardless of how the flow itself is arranged [2].

Nanofluids address this limitation directly: suspending nanoparticles with far higher thermal conductivity than the base fluid raises the heat transfer coefficient through several coupled mechanisms increased effective thermal conductivity, Brownian motion of the particles, altered viscosity and boundary layer thickness, and particle-fluid interaction. Among the available nanoparticle materials, Al_2O_3 is used in this study for its chemical stability and cost-effectiveness relative to metallic alternatives such as Au, Ag, and Cu. Pak and Cho (1998) demonstrated that Al_2O_3-water nanofluid raises h by approximately 45% and 75% at volume fractions of 1.34% and 2.78%, respectively. However, this benefit is not without cost: at 2.78%, viscosity increases by 300%, resulting in a pumping penalty of approximately 31%. At a volume concentration of 3%, the heat transfer coefficient actually falls 12% below that of pure water under constant velocity conditions [3]. This trade-off is why $\varphi = 1.34\%$ is adopted for both validation and the main simulation in the present study, as it captures meaningful enhancement without the penalty dominating.

While these mechanisms are well established for straight-pipe flow, introducing a 180° bend changes the physical picture substantially. As the fluid turns through the curvature, centrifugal force pushes the high-momentum core flow toward the outer wall while pulling low-momentum fluid from the inner wall back toward the core, generating a pair of counter-rotating secondary flows known as Dean vortices within the base fluid itself [4]. When nanoparticles are suspended in this base fluid, they do not follow this secondary motion identically because Al_2O_3 particles (ρ_p = 3880 kg/m³) are roughly four times denser than water (ρf = 998.2 kg/m³), they carry greater inertia and are flung toward the outer wall more strongly than the fluid streamlines carrying them, causing the particles to migrate faster and accumulate more than the base fluid's own secondary flow would produce on its own. This produces a non-uniform particle concentration across the pipe cross-section that a straight pipe would never generate. Since a higher local particle concentration means higher local effective thermal conductivity, this centrifugally driven migration is expected to create a heat transfer coefficient distribution that is fundamentally uneven around the bend elevated at the outer wall, suppressed at the inner wall, and moderate at the side walls rather than the more uniform h typically seen along a straight pipe.

Reynolds number governs how strong these two effects become, rather than acting as a separate mechanism on its own. Higher Re intensifies turbulent mixing and thins the thermal boundary layer, progressively raising h on its own [5]. In a curved pipe, higher Re also raises the Dean number, which scales directly with Re and governs the intensity of the secondary flow described above [6]. A stronger secondary flow at higher Re means nanoparticles are driven toward the outer wall with greater velocity and force, increasing the frequency and intensity of particle-particle and particle-wall collisions along that region so the U-bend effect does not stay fixed as flow rate changes, but is expected to intensify alongside it. This is why the present study tests five Reynolds numbers (10,000-100,000) rather than a single value. Re is the variable that scales both the nanofluid mechanisms and the bend-induced secondary flow, and the range must be wide enough to reveal how strongly the two interact.

Despite existing research on nanofluids and straight pipe flows separately, there remains a limited understanding of how U-bend geometry specifically affects the convective heat transfer coefficient of nanofluids. The change in flow direction and centrifugal forces acting on nanoparticles within the bend are expected to alter the effectiveness of these enhancement mechanisms in ways that are not yet well characterized. Current literature also lacks comprehensive data on the distribution of the heat transfer coefficient along U-bend geometries, both for pure water and nanofluid flows, making direct comparison between straight and curved configurations difficult. Consequently, this study aims to obtain the distribution of the convective heat transfer coefficient along the U-bend for nanofluid flow, thereby providing a comparative analysis of the influence of U-bend geometry on the thermal performance of nanofluids and contributing to the design of more efficient heat transfer systems.

1.2 Problem Statement

It is well established that nanofluids can enhance the convective heat transfer coefficient through several mechanisms, including the increase in effective thermal conductivity of the base fluid, the Brownian motion of nanoparticles, changes in fluid viscosity and thermal boundary layer thickness, and the interaction between nanoparticles and the fluid. However, when the fluid passes through a large curvature such as a 180° U-bend, the influence of these mechanisms is expected to change due to the alteration in flow direction and the centrifugal forces acting on the nanoparticles within the bend. The extent to which this bend-induced flow behaviour alters the convective heat transfer coefficient of Al_2O_3/water nanofluids therefore requires further investigation.

1.3 Research Objective

This study is conducted to obtain the distribution of the convective heat transfer coefficient along the U-bend pipe for nanofluid flow, thereby enabling a comparative analysis of the influence of U-bend geometry on the heat transfer characteristics of nanofluids.

1.4 Benefits

This study provides practical design insights for optimizing U-bend heat exchangers using Al_2O_3-water nanofluids by characterizing the distribution of the convective heat transfer coefficient along the bend geometry. Academically, it contributes to a deeper understanding of how U-bend configurations alter nanoparticle heat transfer enhancement mechanisms compared to straight pipe flows, supporting future development of more efficient thermal management systems.

1.5 Research Scope

The scope of this final project research is as follows:

1) This research uses a two-phase flow approach, with water as the base fluid and Al2O3 nanoparticles.
2) The analysis is performed numerically using Ansys Fluent software.
3) The research model focuses on a 3D 180° U-Bend pipe, assuming steady-state conditions and fully developed flow.
4) The simulation is run under turbulent flow conditions.
5) The nanofluid used has a volume fraction of 1.34%.
6) This study was conducted at a Reynolds number range between 10000, 30000, 50000, 80000 and 100000.

1.6 Report Outline

This study consists of three parts, chapter I is the introduction, consists of topic selection background, research objective, benefit, research scope, and report outline. Chapter II is literature review, which explains various supporting theories related to the final project to be carried out, starting from preparing materials to making samples for testing. Chapter III is methodology, which explains the research working process, starting from modelling the pipe until simulate in software.