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Impact of Different Protrusions in Energy Transfer and Fluid Flow Characteristics Using Al_2O_3 Nanofluid in Pipe Flow

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***Abstract:* -** The study investigates how the protruded surface (the part sticking out of an otherwise flat surface) over the small channel affects flow characteristics and heat transfer within a circular flow regime, utilizing computational methods. This investigation uses an alumina nanofluid to compare and analyze the thermo-physical parameters of protruding pipes such as boxes, cylinders, dimples, and pyramids in pipe flow. Alumina nanofluid with varying volume fractions was evaluated as a thermo-fluid under laminar flow conditions, exploring its ability to enhance energy transmission (heat) over the protruded channels. The protruded surface induces turbulence around the protruded region, altering the coolant's physical characteristics. Since heat transfer predominantly occurs on surfaces, the alteration in surface geometry due to the protruded shape increases detectable heat transfer and the Nusselt number. With an increase in the volume percentage of nanofluids, there's a tendency for pressure loss to rise along the flow direction's centerline. The dimpled channel exhibits the highest Nusselt number among all protruding channels, indicating that increasing the Reynolds number also increases the surface heat transfer coefficient for all protrusions. When compared to the base fluid, cylindrical protrusions show the greatest pressure drop. Additionally, comparing a protruded channel with base fluid to one with a 4% volume of alumina nanofluid, it can be observed that the latter significantly improves heat transfer, followed by volume fractions of 1% to 3%.

Keywords: Protrusions, Nanofluid, Nusselt number, Reynolds number, Laminar flow, Turbulent flow.

1. INTRODUCTION

In the twenty-first century, devices shrank, emphasizing the need for efficient cooling. Nanofluids' thermo-physical traits, especially in forced and free convection, have gained research focus, utilizing "green" nanoparticles to enhance traditional engineering resources. In this investigation, Al_2O_3/water nanofluids with concentrations of 0%, 1%, and 4% are used, and analysis is done on different protrusions in tubes. Double-dimpled corrugated tubes show 20–25% higher heat transfer coefficients with varying nanoparticle compositions, with 3% Al_2O_3-CuO water hybrid nanofluid being the best-performing, outperforming smooth pipes [1]. It examines hybrid nanofluids' fluid flow and thermal performance, revealing that Cu-CuO-water HNFs show the most significant improvement, especially at lower Reynolds numbers [2]. This article presents a multi-objective optimization and prediction approach for wavy microchannel heat sinks, utilizing neural network models with higher accuracy and wider channel width [3]. Proposes a novel optimization approach using machine learning and a surrogate model to optimize spherical dimples in tubes, resulting in increased heat transmission capacity.

The ideal design is a V-shaped dimpled strip, promoting fluid mixing and heat transfer. The study also explores using deep dimple tubes in heat exchangers [4,5]. Explores the impact of dimple structure on liquid droplet entrainment and condensation flow in ethane/propane tubes. It was found that dimple tubes have a more significant heat transfer coefficient and less than 15% inaccuracy between the geometric model and actual fabrication [6, 7]. An experimental study examines the forced magneto-convection of FeO_2/H_2O ferrofluid through dimpled tubes under an alternating magnetic field (f = 5 Hz and B = 0.16 T). The triangle wave type has the lowest heat transfer rate; the square wave type maximizes [8]. Investigates the thermal-hydraulic properties of turbulent flow in conical tubes with dimples, finding high accuracy in a neural network model. It suggests a convergent tube HEX design offers energy efficiency and environmental benefits, potentially reducing CO_2 emissions. Fluid-dimple interactions and flow distribution are related to performance enhancement [9, 10]. Demonstrates that dimples can significantly improve heat transfer efficiency and conduction, with a 27% increase in thermal efficiency and a 29% increase in Alumina nanofluids and the impact of pulsing flow on heat transfer efficiency in a V-shaped

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corrugated channel. Results show that pulsing conditions improve heat transmission and have a higher thermal performance factor (TPF) than constant flow conditions, with values ranging from 0.9 to 1.17 for pulsating corrugated channels and 1.3 to 1.4 for those situations. [11,12]. It compares the hydrothermal performance of wire coils and modified twisted tapes in tubular heat exchangers using hybrid nanofluids. The D-type wire coil has the lowest entropy formation, while V-cut twisted tapes achieve maximum PEC and FOM. Ahmed Ramadhan et al. found that dimples in heat exchanger tubes can result in higher heat transfer rates under the same operating conditions [13, 14]. The Taguchi method is used to predict and optimize multipoint dimple sheet formation in structural steel, and it was found that the dimpled sheet has higher strength than the plain sheet. Ansys simulation software was used to analyze the effects of parameters and the combined impacts of nanofluids and corrugated channels on thermal and hydraulic efficiency [15–17]. The study investigates the thermal efficiency of TiO_2-H_2O nanofluids in double-tube heat exchangers.

Results show that nanofluids can improve heat transfer rate and pressure drop compared to deionized water. This research contributes to developing more efficient energy systems, such as air-conditioning and thermal power plants [18, 19]. The embedded cooling device with a 3D manifold offers single-phase thermal-fluid performance for vehicle power electronics, removing 250 W/cm^2 at 90°C with minimal pressure drop [20]. This article analyzes Al_2O_3-water nanofluids in corrugated channels using a mixture model, revealing that the corrugated channels have the highest average Nusselt number and friction factor [21]. Examines the performance of parabolic trough collectors and sinusoidal-corrugated channels with Al_2O_3-water nanofluid. It finds that placing internal fins in the absorber's lower half improves heat transfer and also investigates the heat transmission of water nanofluids in a sinusoidal wavy channel, showing that nanofluids can significantly improve heat transmission and thermal performance in heat exchangers [22–24]. [25] Demonstrated that dimples on a flat plate increase the Nusselt number, indicating enhanced convective heat transfer due to the induced secondary flow structures. [26] Found that transverse grooves on a heat exchanger surface increased the heat transfer rate by up to 20% compared to a smooth surface. [27] Showed that ribbed surfaces in a cooling channel of a gas turbine blade resulted in a substantial increase in the Nusselt number, improving the overall cooling performance. [28] reported that using dimples in a turbulent flow led to a higher drag coefficient but significantly improved heat transfer rates. [29] Found that the presence of grooves on the surface of a cylinder reduced the drag coefficient by altering the boundary layer characteristics and promoting more streamlined flow.[30] It was shown that ribbed channels exhibited higher friction factors due to increased turbulence, and the substantial heat transfer enhancements made them suitable for compact heat exchangers. [31] Discuss various surface enhancement techniques, including using ribs and grooves in heat exchanger design, highlighting the trade-off between increased heat transfer and pressure drop. [32] provided a comprehensive analysis of the use of ribbed surfaces for blade cooling, showing improved thermal performance in high-temperature environments. Also, suspension stability and thermos-physical properties in hybrid nanoparticles need further investigation despite their limited cost and stability. Further studies on pressure losses and pipe protrusions are required.

Nomenclature

C_p	specific heat (J/kg K)	**Greek Symbols**	
d_f	fluid particle diameter (m)	α	thermal diffusivity (m^2/s)
d_p	nanoparticles diameter (m)	Φ	nanoparticle volume fraction
f	frequency	μ	dynamic viscosity (N s/m^2)
HNF	Hybrid nanofluids	ρ	density (kg/m^3)
k	thermal conductivity (W/m K)	Δp	pressure drop (Pa)
P	pressure (Pa)	**Dimensionless parameter**	
PEC	Performance Evaluation criterion	f	Friction factor
T	temperature (K)	*Nu*	Nusselt number
T_0	reference temperature (273 K)	*Pr*	Prandtl number
u, v	velocities components (m/s)	*Re*	Reynolds number

2. METHODOLOGY

2.1 Physical model

Creating a physical model of different protrusions using CAD softwere and for fabrication by CNC machining or 3D printing [33]in energy transfer and fluid flow involves understanding how these structures affect the behavior of fluids and the transfer of energy within a system. Protrusions, such as fins, ribs, dimples, or other textured surfaces, can enhance heat transfer and influence fluid dynamics [34]. The length of the flow domain is taken to be a mini channel of length 110 mm[35]. The hydraulic diameter of the channel is considered to be 50 mm. The four protrusions, e.g., Box, Cylinder, Dimple, and Pyramid, are used in the model. Base and height are taken at 5 cm and 2.5 cm, respectively. The test portion is demonstrated in the figures below.

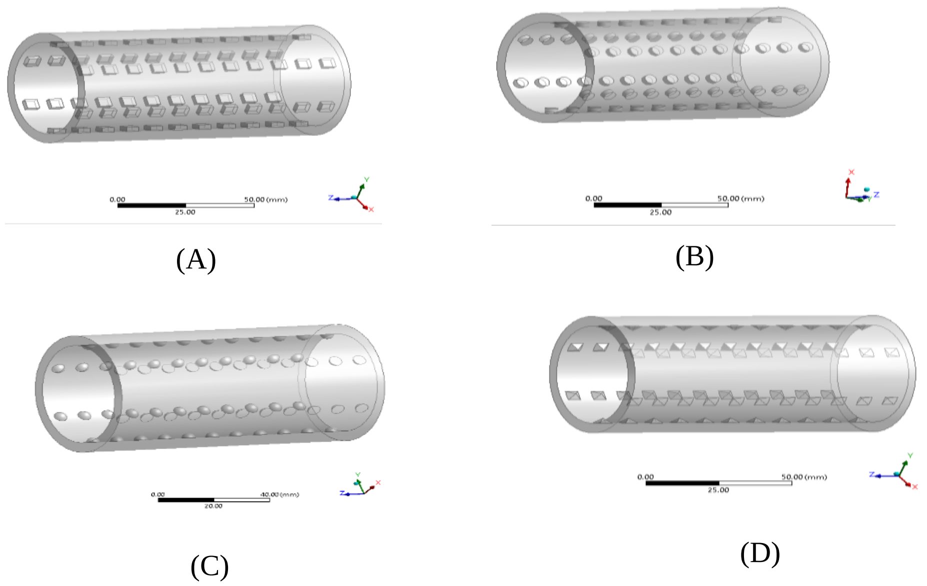

Fig-2.1 Models (A) Box protrusions tube, (B) Cylinder protrusions tube, (C) Dimple protrusions tube, (D) Pyramid protrusions tube

2.2 Configuration of Geometry

The length of the flow domain is considered to be a mini channel of length 110 mm. The hydraulic diameter of all channels is chosen as 50 mm. The dimpled surface numbers are varied by changing the dimples along the span and stream-wise directions. The radius of the dimpled surface is taken to be 2.5 mm. The dimpled diameter is twice the radius. The remaining geometrical height is also 2.5 mm. All models follow the number of protrusions, like several dimples along a stream and spanwise directions. Total number of protrusions in each model is 66.
Creating the fluid domain's grid and meshing is essential to the numerical simulation's accuracy. Tetrahedral cells were implemented during the grid generation, and tetrahedral cells were modified to polyhedral cells to improve accuracy and reduce computational time.

2.3 Thermo-physical Properties of the Nanofluids

The combination of water and Al_2O_3 particles with a diameter of 38 nm is referred to as nanofluid in this study. Tables 1 and 2 present the thermo-physical characteristics of Al_2O_3 nanoparticles and water-based nanofluids, respectively, at a reference temperature of 293 K. Because of the experimental information restriction, the nanofluid density was computed using the classical formula for two-phase flow.

$$\rho_{nf} = \rho_P \, \Phi + \rho_{bf} (1- \Phi) \quad (1)$$

$$(\rho Cp)_{nf} = (\rho Cp)_P \, \Phi + \rho_{bf} (1- \Phi) \quad (2)$$

$$\mu_{nf} = (1+7.3 \, \Phi + 123 \, \Phi^2)\mu_{bf} \quad (3)$$

$$k_{nf} = (4.97 \, \Phi^2 + 2.72 \, \Phi + 1)k_{bf} \quad (4)$$

Table 1:- Thermo-physical properties of Aluminium Oxide (Al_2O_3) and base fluid

	ρ (Kg/m^3)	Cp (J/Kg K)	k (W/m K)

Al_2O_3	3380	773	36
Base fluid (Water)	998.2	4182	0.598

Table 2:- Representation of thermo-physical properties of Aluminium Oxide (Al_2O_3) based nanofluids at different concentrations

Φ	ρ (Kg/m^3)	Cp (J/Kg K)	μ (Pas)	k (W/m K)
0%	998.2	4182	$998e^{-6}$	0.598
1%	1027	4053	$1083e^{-6}$	0.614
4%	1113	3707	$1486e^{-6}$	0.667

Since the nanofluid viscosity directly affects the pressure drop in forced convection, it is an essential parameter for practical applications. For the numerical simulations of nanofluids, equations 1-4 were chosen to compute the thermo-physical behaviors of alumina nanofluids.

2.4 Mathematical Modelling

In the context of mathematical analysis, the Newtonian fluid is regarded as steady-state and incompressible. The flow analysis and heat transfer in the dimpled microchannel flow regime answer the Navier-Stokes equation.

The simulation makes the following assumptions:

(1) Steady-state
(2) Incompressible flow
(3) Uniform dispersion and homogenous mixture of nanoparticles
(4) Spherical nanoparticles with a mean diameter of 38 nm
(5) Laminar flow
(6) Constant fluid characteristic

2.5 Governing equations

The governing equations specified for this particular problem are as follows [36-40]:

a) Continuity Equation:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (5)$$

b) Momentum Equations:

1. In X-Direction:

$$\left(u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y}\right) = -\frac{\partial p}{\partial x} + \frac{1}{Re}\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) \quad (6)$$

2. In Y-Direction:

$$\left(u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y}\right) = -\frac{\partial p}{\partial y} + \frac{1}{Re}\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) \quad (7)$$

c) Energy equation:

$$\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = \frac{1}{RePr}\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right) \quad (8)$$

Here, Re stands for Reynolds number.

$$Re = \frac{\rho V_m d_m}{\mu} \quad (9)$$

Here ρ stands for fluid density, V_m stands for mean velocity, d_m It stands for the hydraulic mean diameter of the channel, and μ stands for the viscosity coefficient of fluid.

d) Heat transfer rate at the channel wall:

$$Q_{nf} = m_{nf} c_{nf} (T_o - T_i) \quad (10)$$

Here, T_0 and T_i indicate the inlet and exit Temperatures, m_{nf} indicates the mass flow rate of the nanofluid, and c_{nf} indicates the heat capacity of the nanofluid.

e) Heat transfer coefficient:

$$h_c = \frac{Q_{nf}}{A_w(\Delta T)} \quad (11)$$

Here, A_w is the surface area. ΔT is the temperature difference.

f) Log mean temperature difference (LMTD) method as:

$$\Delta T = \frac{(T_w - T_o) - (T_w - T_i)}{\ln\left(\frac{T_w - T_o}{T_w - T_i}\right)} \quad (12)$$

g) The Average Nusselt Number is expressed as:

$$Nu = \frac{h_c D_h}{k_{nf}} \quad (13)$$

h) Pressure difference:

$$\Delta P = \frac{fL\rho V^2}{2D_h} \quad (14)$$

i) Friction factor for laminar flow:

$$f = \frac{64}{R_e} \quad (15)$$

j) Required pumping power for laminar flow is calculated by:

$$W = \frac{\frac{\pi}{4} D^2 U_{av} \Delta P}{L} \quad (16)$$

2.6 Boundary conditions

The boundaries considered for the fluid flow simulations in the selected channels are mentioned as follows:

a) At the channel entry point:

Fully developed velocity and constant temperature.

$$u = \frac{3}{2} V_m [1 - \frac{y}{\frac{H}{2}}]^2, \ v = 0 \quad (17)$$

Where, $V_m = \frac{1}{H}\int_{-H/2}^{H/2} u \, dy$, where H is the mean hydraulic diameter

$T = T_i = 293$ K

b) At the walls of the channel:

There is no slip condition, and heat flux is kept constant.

$u = 0$, $v = 0$ and $\frac{\partial T}{\partial y} = q_w$

c) At the channel exit point:

Zero gradient boundaries.

$\frac{\partial u}{\partial x} = 0, \frac{\partial v}{\partial x} = 0$ and $\frac{\partial T}{\partial x} = 0$

$$PEC = (Nu_{enhanced} / Nu_{bf}) / (f_{enhanced} / f_{bf})^{1/3} \quad (18)$$

2.7 Validation of the study

First, the precise dimensions of the dimpled model were simulated using a standard channel in order to validate the model. In order to maintain consistency in the meshing configuration of the smooth and dimpled domains, the normal channel's meshing was carried out using the parallel tree of the dimpled channel. Additionally, the calculated surface heat transfer coefficient was compared to [11] correlation in order to determine the dimpled flow situations.

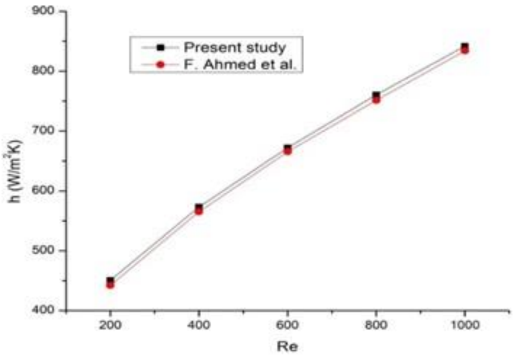

Fig-2.2 Validation of the study by comparing the present study with F. Ahmed et al.

3. RESULT AND DISCUSSION

3.1 Grid independence study-: Grid independence study validates numerical simulations in computational fluid dynamics, ensuring grid size or resolution doesn't impact outcomes. The Grid independence test takes water as a working substance with a constant heat flux of 10 kW/m^2[41]. Several elements have been changed in different meshing to calculate the Nusselt number. Reynolds's number has been kept constant at 400.

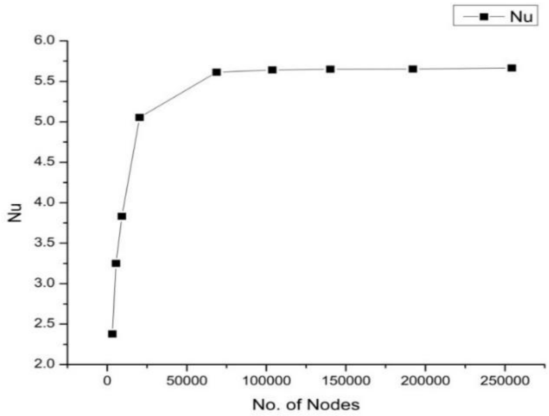

Fig-3.1 Variation of Nusselt number with grid size

The computation is carried out by ANSYS Fluent utilizing the Finite Volume Method. The improvement in the number of nodes and element size is calculated from the initial cell size of the fluid domains to the final cell size in the fluid domains. In this paper, a 1mm element size (Node-254343, Element-1430463) indicates the best possible result, as shown in the above graph Fig 3.1. The selected mesh model with a 1mm element size is chosen for further simulations of different test cases.

3.2 Thermal and hydraulic performance for different channel design

Evaluating channels' thermal and hydraulic performance with various protrusions is critical in optimizing energy transfer and fluid flow in applications such as heat exchangers, cooling systems for electronic devices, and other thermal management systems. Different protrusions—such as dimples, ribs, pin fins, and other microstructures—can significantly influence fluid flow's heat transfer enhancement and pressure drop characteristics through these channels[42]. The thermal performance of channels with protrusions is typically evaluated in terms of the Nusselt number (Nu), representing the convective heat transfer relative to conductive heat transfer. Protrusions increase the Nu by disrupting the boundary layer, promoting mixing, and enhancing turbulence[43]. Under the laminar flow assumption, a numerical inquiry was conducted for Box, Cylinder, Dimple, and Pyramid flow channels to analyze the Nusselt number (Nu_{avg}) change and friction coefficient (f). The value of Re was varied from 200 to 2000. In order to examine the effects and functionality of the surface of the different protrusions by flowing nanofluids with various concentrations. Heat transfer is increased due to the flow blockages caused by the protruded surface. Additionally, because of the protruded surface, turbulence around the protruded region over a fluid pattern affects the coolant's physical properties.

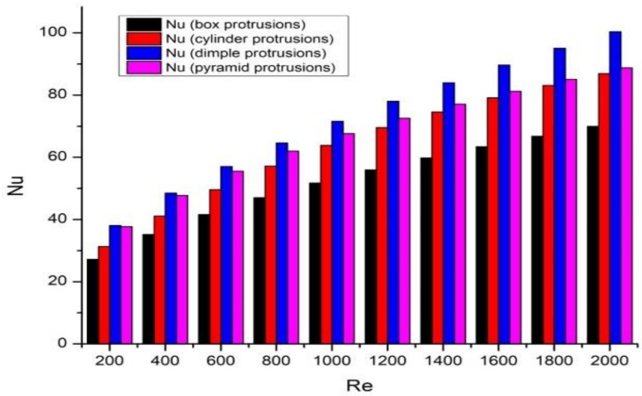

Fig-3.2 Re v/s Nu for different Protruded surface (Φ=1%)

Heat transfer is a surface phenomenon; hence, the surface modification brought about by protruded shape contributes to the rise of detectable heat transfer and Nusselt number. It can be seen from Fig-3.2 that in all four protruded surfaces, the dimpled shape provides greater Nu at all Reynolds numbers.

The relation of the heat transfer coefficient and Reynolds number is shown in Fig-3.3, indicating that we can get maximum surface heat transfer coefficient in dimpled protrusions. In comparison to all four protrusions, dimpled protrusions give promising results. The graph also indicates that increasing the Reynolds number increases the surface heat transfer coefficient for all protrusions.

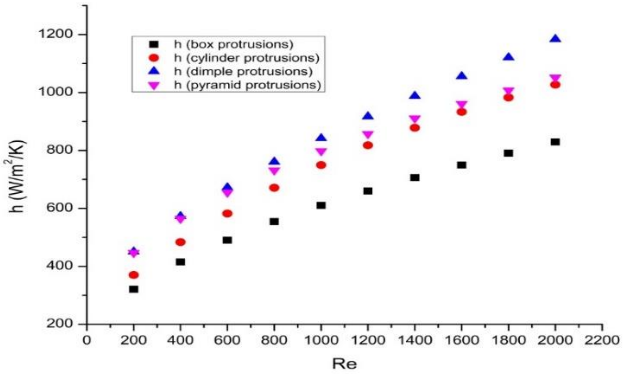

Fig-3.3 Variation of h (W/m^2) at different Re with 1% volume fraction

3.3 Thermal Performance Analysis

The thermal performance of different protrusions in energy transfer and fluid flow has been extensively studied due to their effectiveness in enhancing heat transfer. Protrusions such as dimples and ribs disrupt the boundary layer, increasing turbulence and heat transfer rates.

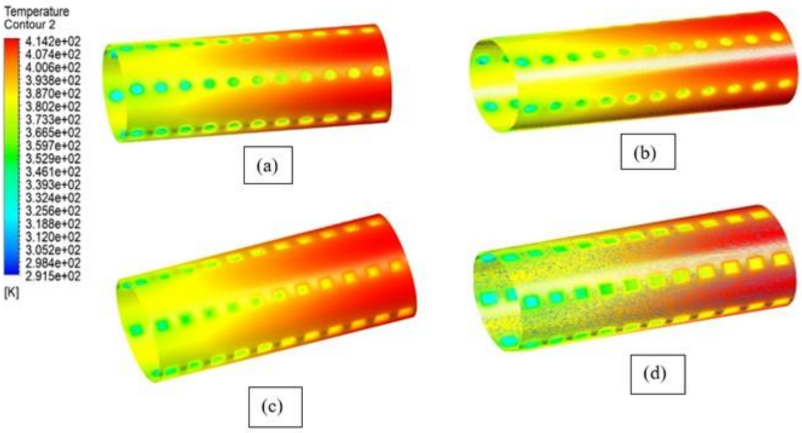

Fig-3.4 Temperature distribution of (a) Box, (b) Cylinder, (c) Dimple, (d) Pyramid Protruded tube (Re = 1200, Φ = 1%)

The temperature distribution across the fluid domain and at the flow output can be shown in Fig. 3.4. Positive effects are assessed on the bulk temperature and the nanofluid wall temperature with respect to the base fluid because of the suspension of nanoparticles in the base fluid. This influence ultimately results in the enhancement of heat transmission. Furthermore, it can be demonstrated that a rise in the volume percentage of nanoparticles decreases both the bulk and wall temperatures, hence improving heat transfer. Because of the combination of nanoparticles with better thermal conductivities, the coolant's thermo-physical properties improved when compared to the base fluid, allowing for the identification of the improvement in heat transfer.

3.4 Flow Characteristics Analysis

Analyzing the flow characteristics of different protrusions using various nanofluids involves understanding how protrusions affect the fluid flow and heat transfer properties. Protrusions can include shapes like ribs, dimples, or other surface modifications, and the nanofluids can be composed of different base fluids with nanoparticles such as Al_2O_3 and CuO. The study reveals that a 1% volume fraction of alumina nanofluids can attain fully formed laminar flow at the earliest development length, with the development length growing as the Reynolds number increases. The velocity profile remains unchanged with nanoparticles, suggesting their presence doesn't significantly affect flow regime velocity.

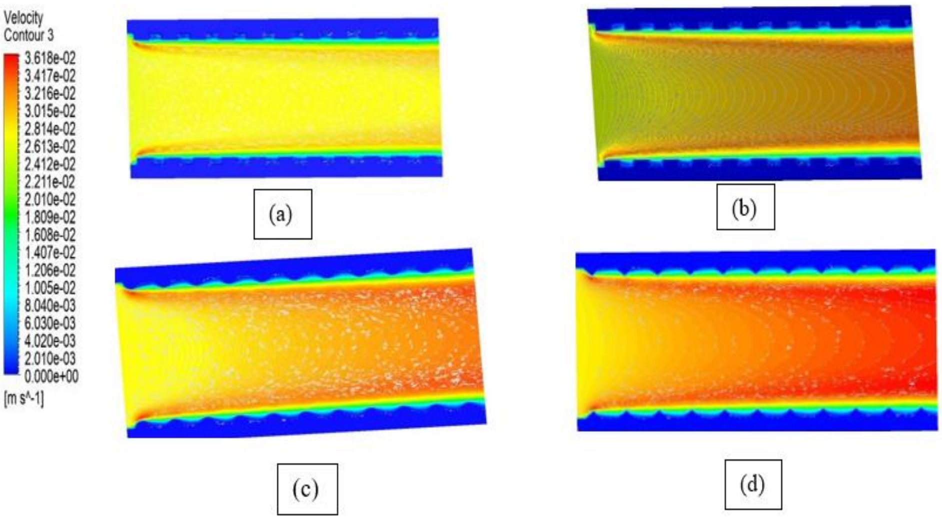

Fig-3.5 Variation of velocity for (a) Box, (b) Cylinder, (c) Dimple, (d) Pyramid protruded channel at Re 1200, Φ=1%

3.5 Performance analysis using Al_2O_3 Nanofluid as coolant

The study aimed to determine how adding nanoparticles to the base fluid affected the heat transfer coefficient and friction factor along the flow channel. Al_2O_3-based nanofluid is taken into account for the analysis. The nanoparticles are believed to have a mean diameter of 38 nm and are spherically formed. The single-phase flow regime is considered, and the particles are assumed to be evenly mixed with the coolant. The study uses the effects of 1% and 4% volume fractions over base fluid as tests for different protruded surfaces. They are selected for more research in light of the computing demands made throughout the simulation.

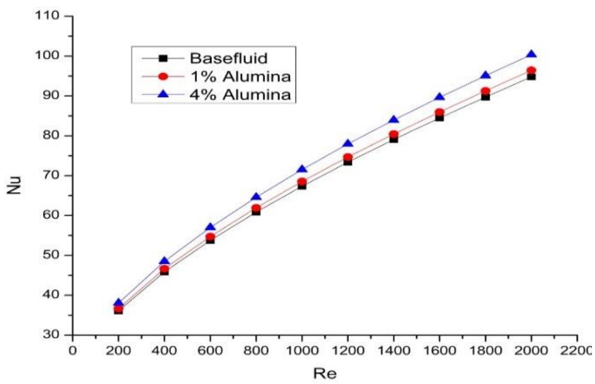

Fig-3.6 Re v/s Nu in dimpled tube for Φ = 0 to 4%

3.6 Effects of modified Channel design and fluid variation on ΔP and f

The effects of modified channel design and fluid variation on pressure drop (ΔP) and friction factor (f) of different protrusions using different nanofluids have been a topic of significant research interest. This topic is relevant for enhancing microchannels' heat transfer efficiency and performance in various industrial applications. Protrusion in the channels, such as dimples or ribs, can improve heat transfer by disrupting boundary layers and increasing turbulence[44]. One of the critical indicators of the effectiveness of the nanofluid application is pressure drop. Pressure decrease and coolant pumping power have a strong relationship. As the volume percentage of nanofluids increases, the pressure drop tends to grow along the flow direction, as shown in Fig - 3.7. It demonstrates that the dimpled channel with a 4% volume fraction has the most significant pressure drop, followed by the dimpled channel with a 1% volume fraction. The pressure distribution at the fluid domain's centreline indicates this.

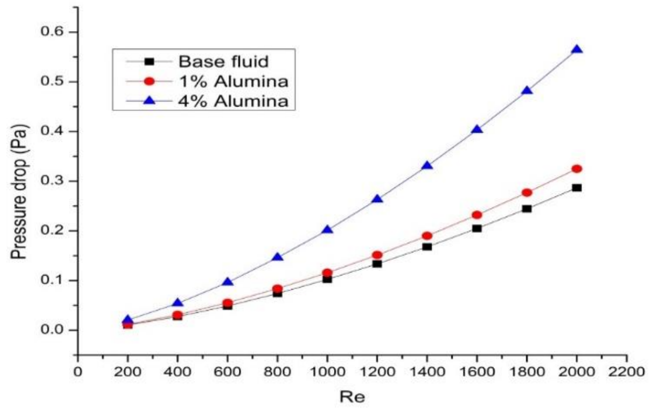

Fig-3.7 Pressure drop for different concentrations of Nano-fluid along the centreline at different Reynolds number in dimple tube

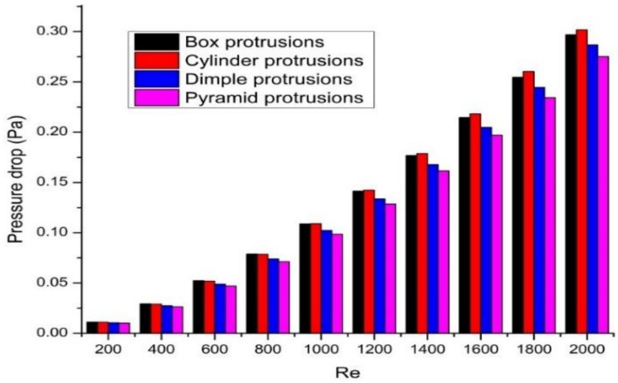

Fig-3.8 Comparisons of pressure drop in different protrusions (Φ = 0 %)

However, Fig-3.8 shows that, with a slight fluctuation, the dimpled and the dimpled channels with 1% and 4% volume fractions of nanofluid exhibit very near proximity to each other. An explanation could be given regarding the density variation (ρ). Although the pressure drop increases as the volume fraction increases, it is not significant enough to significantly alter the total friction factor since it is considered a tiny channel, resulting in a lower pressure drop. On the other hand, the fluid's density rises due to the increased volume percentage, which evidently decreases the friction factor. As a result, the density and pressure drop increase and balance one another out, causing the friction factor to vary slightly.

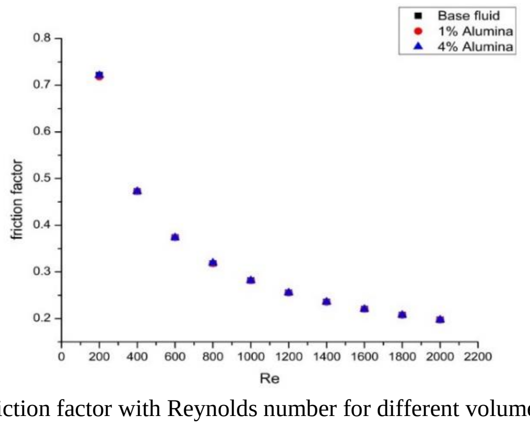

Fig-3.9 Variation of friction factor with Reynolds number for different volume fractions of nanofluids

3.7 Performance evaluation criterion

Modifying channel designs with various protrusions and using different nanofluids can significantly enhance thermal performance, but this comes with a trade-off in terms of increased pressure drop and pumping power[45]. The optimal channel design and nanofluid combination depends on the specific application and desired balance between heat transfer efficiency and energy consumption. Nanofluid improves heat transport in protruded tubes but requires a higher pressure drop. Performance evaluation criterion (PEC) evaluates thermo-hydrodynamic performance, but a decrease in layer thickness hinders pressure drop optimization.

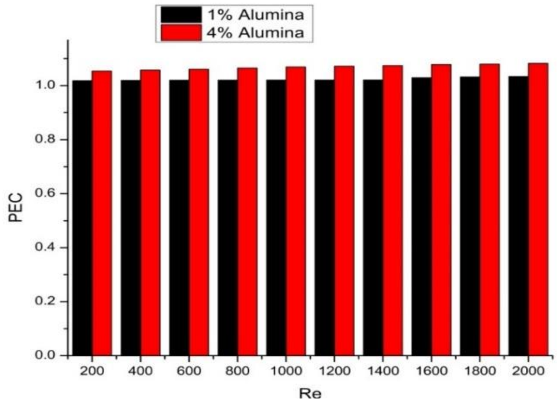

Fig-3.10 PCE variation in dimple tube at Φ= 1% and 4%

The performance of nanofluids with larger PEC ratios indicates that their heat transfer performance surpasses air resistance. Compared to the dimpled channel with base fluid, the results suggest that the maximum thermal performance is achieved at a volume fraction of 4%, followed by 1%. The findings are shown in Fig.3.10, and it is possible to conclude that adding nanoparticles can raise the coolant's performance evaluation criterion (PEC).

3. CONCLUSIONS

The effects of modified channel design on the performance evaluation of different protrusions using various nanofluids involve a multifaceted analysis, integrating fluid dynamics, heat transfer, and material science. Here's an overview of how these modifications and nanofluids can influence performance metrics such as heat transfer coefficient, pressure drop, and overall thermal efficiency. Numerical investigations were carried out for all four protruded channels for several test situations. The study indicated that a dimpled channel could improve heat transfer compared to all four channels. The thermo physical characteristics of the thermo fluid are enhanced by the addition of Al_2O_3 nanoparticles to the base fluid.

- Increasing the complexity of channel design generally increases ΔP due to higher frictional losses.
- Using nanofluids can either increase or decrease ΔP depending on the balance between enhanced thermal properties and increased viscosity.
- In comparison to a protruded channel with base fluid, it can be observed that a protruded channel with a 4% volume of alumina nanofluid can improve heat transfer, followed by a 1% volume fraction.
- The pressure drop rises along the flow direction's centreline as the volume percentage of nanofluids rises.
- In all protruded channels, the dimpled channel shows the highest Nussenlt number.
- Pressure drop is highest in cylindrical protrusions as compared to base fluid.
- Compared to the dimpled channel with base fluid, the results indicate that the maximum thermal performance (PCE) is achieved at a volume fraction of 4%, followed by 1% alumina nanofluid.
- The friction factor at 1% and 4% volume fraction of nanofluid exhibits very close to each other with a slight variation.

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