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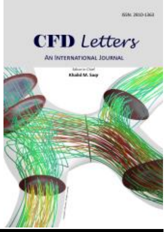

Evaluation of Heat Transfer and Fluid Dynamics across a Backward Facing Step for Mobile Cooling Applications Utilizing CNT Nanofluid in Laminar Conditions

Afrah Turki Awad[1,2,*], Abdulelah Hameed Yaseen[3], Adnan M. Hussein[2]

[1] Renewable Energy Research Center - Kirkuk, Northern Technical University, Iraq
[2] Mechanical Power Techniques Engineering, Technical Engineering College/ Kirkuk, Northern Technical University, Iraq
[3] Dept. of Petroleum Eng., College of Eng., Al-Kitab University, Kirkuk, Iraq

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ABSTRACT

In a variety of engineering applications, the efficacy of heat dissipation in mobile cooling systems is greatly influenced by the Backward Facing Step. Its significance in optimizing cooling solutions for mobile devices is highlighted by the fact that its design and fluid dynamics are crucial in minimizing skin friction and improving passive heat transfer. In this paper, we present a verification of an advanced numerical model for heat transfer and fluid flow through a Backward Facing Step, used in mobile cooling. The objective of this study is to explore fluid separation, a method enhancing passive heat transfer and reducing skin friction. ANSYS/FLUENT software has been used to solve the backward facing step in a horizontal duct filled with pure water. Carbon nanotube (CNT) dispresed into the base fluid at different volume fractions of 0.2%, 0.65%, and 1%. This study focused on laminar flow conditions ranging from Reynolds numbers 200 to 900. In order to reduce the computation time and ensuring the accuracy and reliability of numerical simulations, a grid independence study has been conducted. The findings revealed a substantial rise in the average Nusselt number and heat transfer coefficient with increased Reynolds number and volume fraction of nanoparticles. Specifically, the nanofluid (CNT/water) exhibited the highest average Nusselt number and heat transfer coefficient with volume fractions 1%. Furthermore, the research showed a decrease in the skin friction factor as both Reynolds number increased and nanoparticles' volume fraction decreased. The increments of nanoparticles' concentrations lead to increase viscosity, promotes agglomeration, alters flow behaviour by inducing turbulence, and enhances heat transfer. These factors collectively contribute to higher skin friction due to increased resistance to fluid flow and disrupted streamline patterns.

1. Introduction

The occurrence of flow separation and reattachment due to the sudden expansion of fluid flow through backward-facing steps has been identified as a critical industrial situation as mentioned in the previous study [1]. Heat transfer applications are prevalent in internal flows like combustors and

* *Corresponding author.*
E-mail address: afrah.turki@ntu.edu.iq (Afrah Turki Awad)

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external flows such as gas turbine engines, aircraft, buildings, chemical processes, and various heat transfer devices. Understanding flow separation and reattachment is crucial for assessing flow characteristics and influencing heat transfer mechanisms. In the reattachment area of these devices, significant mixing of low and high fluid energy occurs, as studied by the literature [2]. Islam *et al.,* [3] state that 3-D CFD was utilised to look at the ideal twist angle, Reynolds number impacts, and wing performance.

Flow over the backward-facing step (BFS) is complex, involving multiple instabilities. Previous studies, focusing on key flow properties in horizontal BFS geometry, have categorized flow disturbances into three primary zones according to the study by literature [3]. These comprise the reattachment zone, shear layer region, and separation bubble or recirculation zone in BFS as conducted by previous study [3].

Literature suggests that the evaluation of glide separation and reattachment thru the BFS become initiated inside the 1950s. In the beyond decade, there was extensive attention on studies associated with separate float.

Goldstein *et al.,* [4] performed experimental studies investigating the reattachment point for laminar and subsonic fluid glide over a step. Their findings revealed that versions inside the Reynolds number result in adjustments in reattachment positions and boundary displacement thickness based on the literature examine [4].

Over the past few decades, several experiments and numerical simulations were conducted on inner fluid flows involving separation and reattachment. These investigations spotlight the effectiveness of utilizing the backward going through steps approach in one-of-a-kind orientations and with numerous factors like baffles, ribs, and grooves to depict diverse boundary conditions primarily based on a review of the literature [5]. Moreover, a have a look at published in the literature [6] discovered that carbon nanotubes outperform distilled water in phrases of thermal performance and lower absorber temperature.

Numerical simulations have been performed to have a look at warmth transfer and turbulent fluid float the use of the BFS and exclusive corrugated partitions. When a corrugated wall was combined with the BFS at Re = 5000, the Nusselt range (Nu) improved by way of 62% is taken from the preceding look at [7].

Many researchers from the previous examine [8-12] have explored the use of nanofluids. In a numerical evaluation of warmth switch thru the BFS, diverse concentrations and kinds of nanoparticles were introduced into the bottom fluid. Across the whole variety of Reynolds numbers, there has been a widespread increase in the common Nusselt variety with the nanoparticle concentration as performed by the look at [13].

Additionally, a test turned into conducted to analyse the effect of turbulent βGa_2O_3/water nanofluid waft thru the microscale backward-facing step (MBFS). Compared to the bottom fluid, a huge increase inside the Nusselt wide variety turned into discovered with the aid of the study [14]. The study explored pressured convection with Al_2O_3/water nanofluid interior a horizontal duct with a BFS. The Nusselt range rose with better Reynolds numbers and increasing nanoparticle volume fractions as indicated from the previous observe [15]. Investigating float and warmth switch properties, a computational model analysed blended convective laminar fluid float over a 3-dimensional MBFS with a Reynolds variety of 35. Glycerine as the base fluid yielded the best Nusselt range, at the same time as water caused a greater skin friction coefficient is taken from the preceding have a look at [16]. Another numerical study tested turbulent and laminar drift, as well as warmth switch, for Cu/water nanofluid flowing throughout a BFS. Heat transfer elevated with higher Reynolds numbers and concentrations, highlighting the step's recirculation glide and enhanced warmth transfer, it become obtained from the earlier research [17].

A earlier study [18] indicated that a Tesla valve with an unusual geometry can be optimised numerically for warmth transfer and fluid waft, and that particular predictions could be made using genetic algorithms and synthetic neural networks.

As previously mentioned in the study [19–20], nanoparticles have been added to the composite material to enhance its characteristics. Moreover, the TiB2-SiC and TiB2-SiC-GNP composites that were chosen for use in high-temperature heat exchangers were from an earlier work [21]. Based on the results of the previous study [21], it was discovered that these composites improved thermal performance, attaining an 8.2% efficiency gain over Al_2O_3. Moreover, graphene nanoplatelets (GNP) were employed as reinforcements in aluminium alloys by Rahim *et al.,* [22]. The previous study [22] was utilised to get optimal results, which involved 0.9wt% GNP and 180 minutes of heat treatment to enhance mechanical properties.

As demonstrated by earlier research, investigations and CFD simulations of nanoparticles incorporated into a phase-changing material demonstrated benefits for high-temperature applications [23, 24]. Additionally, from the earlier study [25], the Nusselt number and pressure drop in a bionic fractal heat sink optimised using ANN and RSM models are taken. The previous work [25] provides an optimisation of bionic fractal MCHS with trapezoidal cavities for heat transmission through the use of ANN and RSM models. The study also reveals the influence of material on performance. In their investigation of indoor thermal comfort and energy consumption in Cairo's educational buildings, Fahmi *et al.,* [26] offer a variety of insulating materials and thicknesses for the best possible performance and economy.

This study closes a significant knowledge and application gap regarding fluid separation for passive heat transfer in mobile cooling. The study's findings and the validated numerical model have the potential to significantly advance the design and execution of creative cooling solutions for mobile devices and other gadgets. Moreover, in this study, an in-depth examination of heat transfer and fluid dynamics within BFS is meticulously carried out. The primary purpose of BFS lies in its ability to function as a miniature channel for effectively cooling mobile devices. This comprehensive approach not only explores the intricacies of heat transfer and fluid flow within BFS but also provides a robust foundation for understanding its applications in mobile device cooling. Therefore, Ansys-Fluent (version 2020 R1) was used to conduct numerical simulations with various mesh sizes, optimizing grid resolution. In this study, Reynolds numbers range from 200 to 900 for laminar flow. Carbon nanotube (CNT) with different concentrations (0.2%, 0.65%, and 1%) have been studied. Nusselt numbers and friction factors were computed using data from the previous experimental study [27-30]. In this study, a performance evaluation criteria (PEC) has been conducted. These simulation results will contribute to the design and performance analysis of horizontal backward-facing steps.

2. Methodology

2.1 Geometry of Simulated Model

The geometry, illustrated in Figure 1, has been chosen to study the flow over the backward-facing step. The setup consists of a rectangular input channel followed by a 1.7 mm backward-facing step on the floor. The height of the inlet duct is 1.7 mm, and the height of the duct after the step is 3.4 mm, as shown in Figure 1. These dimensions were selected based on the previous study [28]. Therefore, a comparison between our numerical results and the experimental results taken from the previous study [28] can be performed.

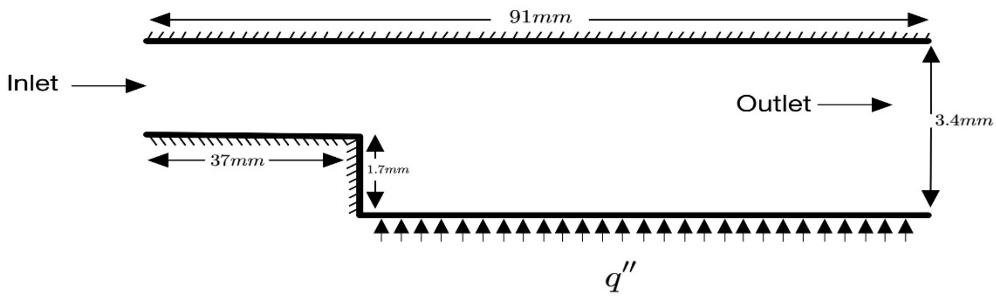


Fig. 1. Schematics of the backward-facing step

2.2 Grid Independence Study

The independence test grid was utilized to determine the most suitable grid computation and its impact on the results. Three alternative computational grids were considered using mesh sizes (0.2 mm, 0.15 mm, and 0.05 mm), as shown in Table 1. The average Nusselt number was plotted downstream of the heated wall's step using all three grids. The grid independence test revealed that the results were closely aligned, with a local Nusselt number deviation of only 0.75 % for all three grids. From Table 1, Mesh 3 was selected as it provided the optimal outcome within the shortest timeframe. Figure 2 illustrates the selection of the optimal mesh based on another experimental study, and Figure 3 displays the mesh distribution of the computational domain.

Table 1
Selected the optimum mesh

Mesh	Element size	Number of elements	Inflation layer	Nusselt number
M1	2 e^{-4}	12409	10	8.995
M2	1.5 e^{-4}	21679	10	9.374
M3	5 e^{-5}	128831	12	8.075

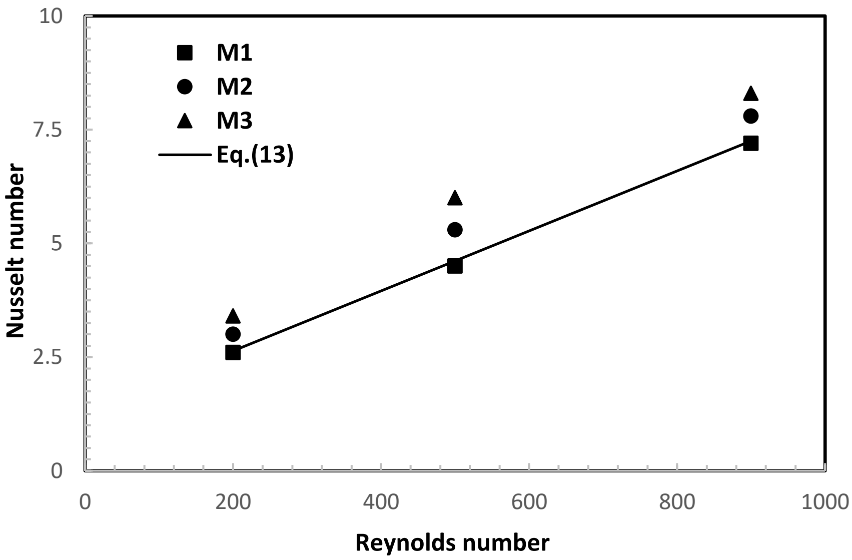


Fig. 2. Mesh independent study

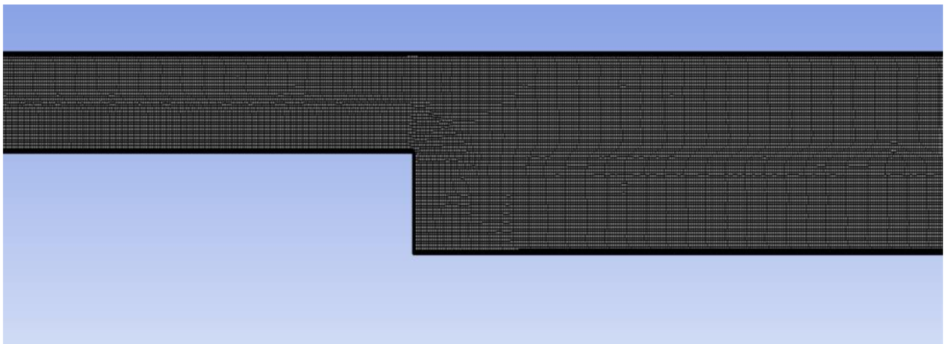


Fig. 3. Mesh distribution of the computational domain

2.3 Numerical Methodology

In this study, the analysis of heat transfer enhancement was conducted using a CFD simulation program solver, ANSYS/FLUENT (version 2020-R1). The finite volume technique was employed for discretization of the fluid flow equations, encompassing mass, momentum, and energy conservation, as described in Eq. (1) – Eq. (3) [31].

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \tag{1}$$

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{1}{(1-\phi)+\phi\frac{\rho s}{\rho f}}\frac{\partial P}{\partial X}+\frac{1}{\mathrm{Re}}\frac{1}{((1-\phi)^{2.5}((1-\phi)+\phi\frac{\rho s}{\rho f}))}\times\left(\frac{\partial^2 U}{\partial X^2}+\frac{\partial^2 U}{\partial Y^2}+\frac{\partial^2 U}{\partial Z^2}\right)+\frac{Gr_x}{R^2}\vartheta \tag{2}$$

$$U\frac{\partial \vartheta}{\partial X}+V\frac{\partial \vartheta}{\partial Y}+W\frac{\partial \vartheta}{\partial Z}=\frac{1}{\mathrm{Re}\,\mathrm{Pr}}\left(\frac{\frac{k_{nf}}{k_f}}{(1-\phi)+\phi\frac{(\rho Cp)s}{(\rho Cp)f}}\right)\left(\frac{\partial^2 \vartheta}{\partial X^2}+\frac{\partial^2 \vartheta}{\partial Y^2}+\frac{\partial^2 \vartheta}{\partial Z^2}\right) \tag{3}$$

Where φ represents the concentration of nanoparticles. The densities of fluid and solid are ρ_f, ρ_s in k/m^3, respectively.

A discretization formula was employed and solved numerically using laminar modelling analysis. The coupled method was used to link the pressure and velocity fields. For discretizing the continuity, momentum, and energy equations, the second-order upwind technique was utilized. The solution was considered convergent when all residual values approached 10^{-4}. The fluid flow exhibited a parabolic velocity profile at the inlet of the channel, far upstream of a step, and became fully developed hydrodynamically at the exit, far from the heating zone of the bottom wall. It was assumed that the channel walls, except for the heating part of the bottom wall, were thermally insulated. The friction factor and pressure drops for fully developed flow through the channels were determined according to Eq. (4) – Eq. (8) [32]:

$$\Delta p=\Delta p_{in,out}-p_d \tag{4}$$

$$p_d = 1.18\rho \times u^2{}_{ave} \tag{5}$$

$$u_{ave} = \frac{m^o}{\rho A_c} \tag{6}$$

$$\mathrm{Re} = \frac{u_{ave} D_h}{\upsilon} \tag{7}$$

$$f = \Delta p.\frac{D_h}{L}.\frac{2}{\rho u^2{}_{ave}} \tag{8}$$

The base fluid was loaded with the nanoparticles (CNT) at volume fractions of 0.2%, 0.65%, and 1%, respectively. The properties of nanofluid have been estimated by the use of Eq. (9) - Eq. (13) [33]:

$$\mu_{nf} = \frac{\mu_f}{(1-\phi_1)^{2.5}} \tag{9}$$

$$(\rho Cp)_{nf} = (1-\phi)(\rho Cp)_f + \phi(\rho Cp)_p \tag{10}$$

$$\rho_{nf} = \phi\rho_p + (1-\phi_v)\rho_f \tag{11}$$

$$\frac{k_{nf}}{k_f} = \frac{k_p + 2K_f - 2\varphi(k_f - k_s)}{k_p + 2k_f + \varphi(k_f - k_s)} \tag{12}$$

$$Nu = 0.023\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.3} \tag{13}$$

Where C_p represents the specific heat capacity (J/kg. K), g is the gravitational acceleration (m/sec^2), K is thermal conductivity (W/ m. K), Nu is the nusselt number, D_h is hydraulic diameter (m), Pr is prandtl number, Re is Reynolds number, h is heat transfer coefficient (W/m^2). Furthermore, thermophysical properties of pure water and nanofluid are mentioned in Table 2.

Table 2
Thermal properties of pure water and nanoparticles [34]

Material	ρ (kg/m^3)	$Cp(kJ/kg.K)$	$k(W/m.K)$	$\mu\,(N/m.s)$
H_2O	997.1	4179	0.613	0.001004
CNT	1298	705	3650	-

Performance evaluation criteria (PEC) can be calculated using the Eq. (14):

$$PEC = \frac{(\frac{Nu_{nf}}{Nu_f})}{(\frac{f_{nf}}{f_f})^{1/3}} \tag{14}$$

The solver type is pressure-based, and the solving algorithm is simple. Under-Relaxation Factor values were found to be 0.3.

3. Validation of the Results

Figure 4 compares the experimental data [28], the mathematical calculations based on Eq. (13), and the current CFD results for various average Nusselt numbers across a Reynolds number range of (200-900). The comparison clearly demonstrates that our current numerical data follows a similar trend to that observed in Ref. [28] and Eq. (13).

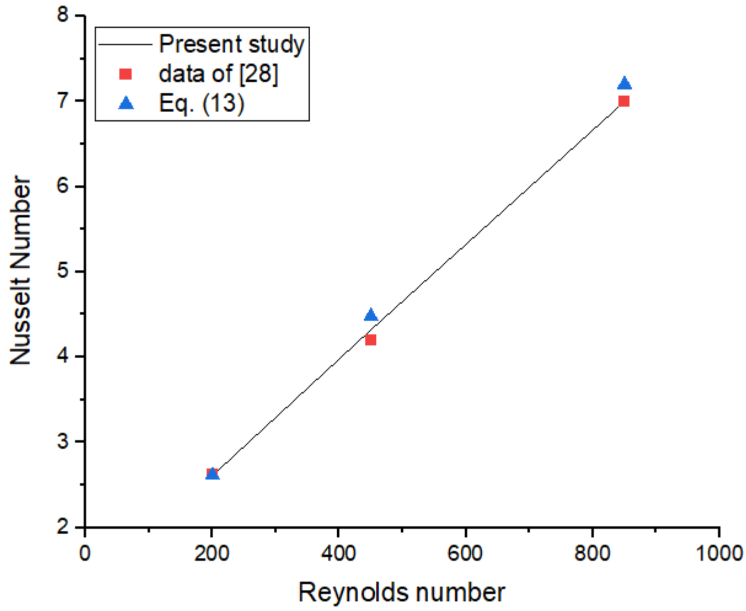


Fig. 4. Validation of Nusselt number present data with experimental results of Ref. [28], calculated from Eq. (13), and the present CFD study for 1% nanofluid concentrations

4. Results and Discussion

This section presents the results of numerical simulations, specifically focusing on the distributions of Nusselt numbers, skin friction coefficient, and Performance evaluation criteria (PEC). The CFD analysis of CNT/water nanofluid flowing through the backward facing step has been conducting.

The numerical analysis investigates the impact of increasing Reynolds numbers on average Nusselt number enhancement for Re: 200 to 900. The results, depicted in Figure 5, demonstrate a direct correlation between nanoparticles' volume fractions and Nusselt number. It is observed that the Nusselt number values increase with the increase in volume fraction, this is similar to the findings taken from the previous study [35-37]. Specifically, the CNT-nanofluid with a 1% volume fraction exhibits the highest average Nusselt number. Higher nanoparticle concentrations in nanofluids contribute to an increase in the Nusselt number through mechanisms such as enhanced thermal conductivity, increased turbulence promoting convective heat transfer, improved heat dissipation capabilities of nanoparticles, and the alteration of the thermal boundary layer near the solid surface, collectively resulting in more efficient heat transfer.

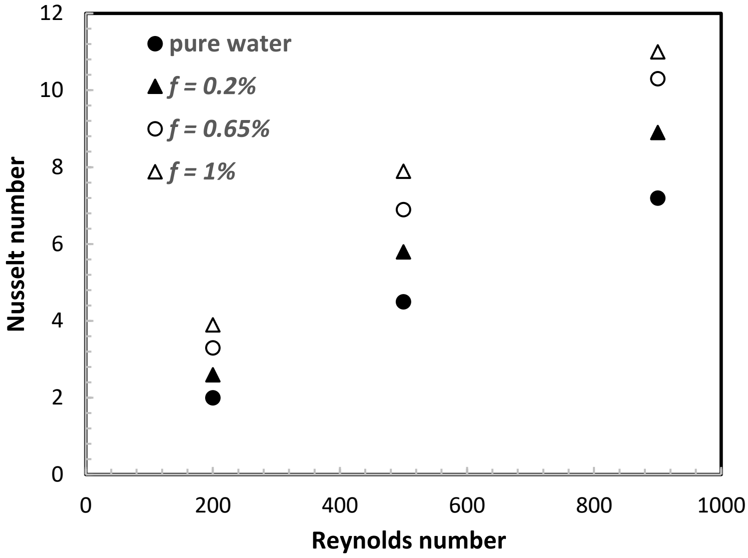


Fig. 5. Numerical results of base fluid vs. nanofluid concentration effects on Nusselt number

As shown in Figure 6, increasing the nanoparticles' concentrations and Reynolds number significantly improves the skin friction coefficient. It can be seen that the values of skin friction coefficient increase with increasing of nanofluid volume concentrations but decreasing with increasing of Reynolds number and the maximum values of skin friction coefficient indicated as 1% CNT-nanofluid. The reason of this behaviour is related to increase of viscosity which affected to skin friction factor. The skin friction coefficient tends to increase with higher nanofluid volume concentrations due to enhanced thermal conductivity and changes in viscosity associated with increased nanoparticle concentrations. Conversely, it decreases with rising Reynolds numbers as turbulent flow and reduced boundary layer thickness mitigate viscous forces, and nanoparticles can sometimes suppress turbulent structures, contributing to a lower skin friction coefficient.

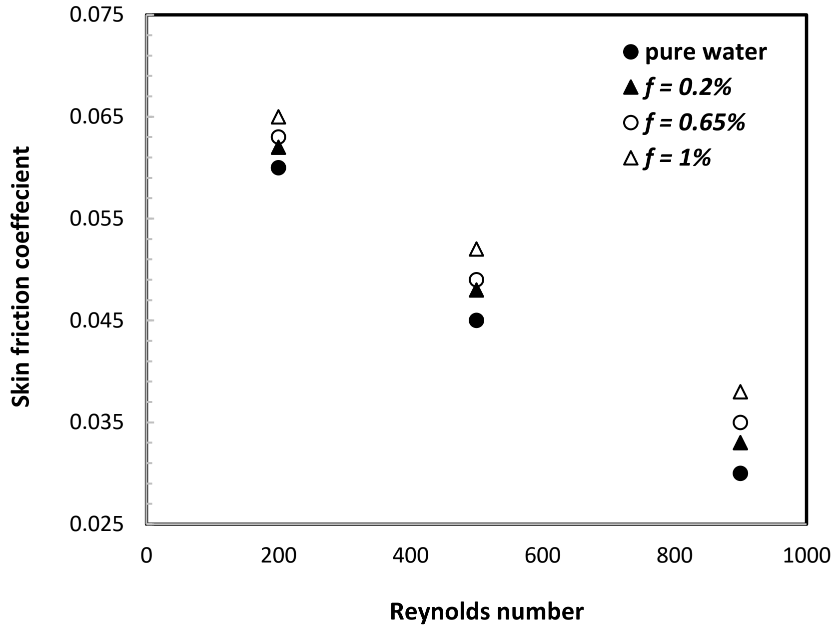


Fig. 6. The numerical results of base fluid vs. nanofluid concentrations effect on friction factor

It is evident that the Nusselt number and skin friction coefficient are significantly influenced by the type of base fluid, and concentration of nanoparticles used. The CNT-nanofluid exhibited the most substantial improvements when the concentration was increased to 1% compared to 0.2%. This improvement can be attributed to the enhanced properties derived from the higher concentration of nanoparticles dispersed within the base fluid.

According to Sudarmadji *et al.,* [37], the Performance Evaluation Criteria (PEC) determine the feasibility of a system for increasing heat transfer. A PEC less than 1 implies inefficiency, PEC equal to 1 indicates no impact, and a PEC greater than 1 suggests the system is feasible and effective in practical applications for enhancing heat transfer [28]. Figure 7 displays the PEC; it was observed that the increase in CNT-nanofluid concentrations is significant for increasing PEC.

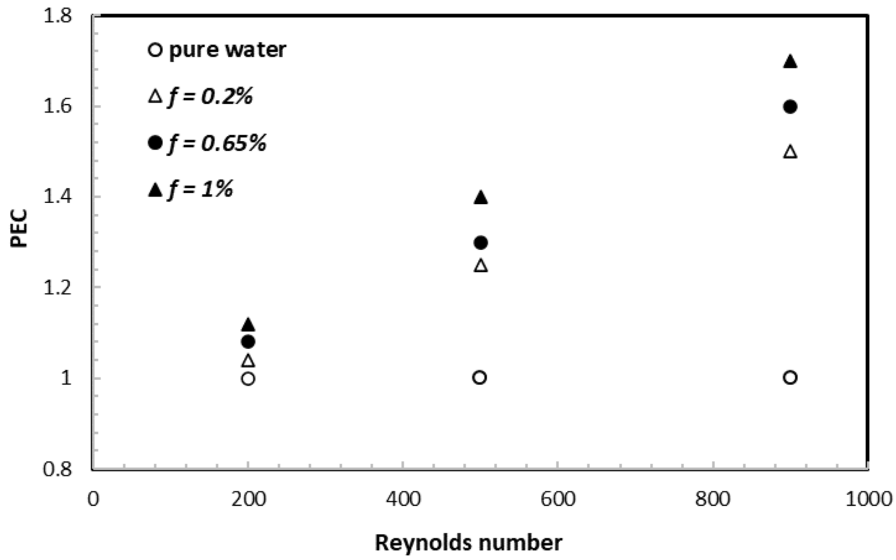
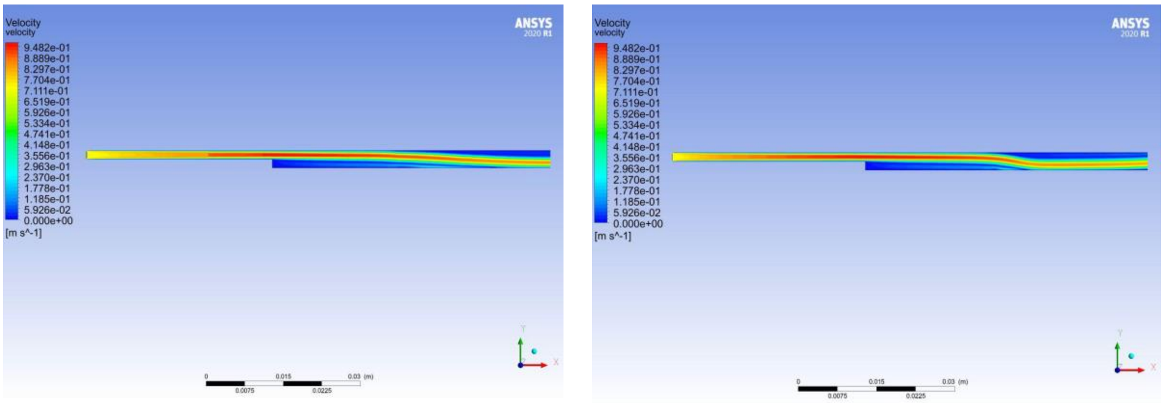


Fig. 7. The performance evaluation criteria (PEC) against Reynolds number with different nanofluid concentrations

Figure 8 illustrates the contours of velocity distributions for (a) the pure water and (b) the 1% nanofluid. Notably, the nanofluid exhibits lower velocities compared to pure water, attributed to its higher density and viscosity.



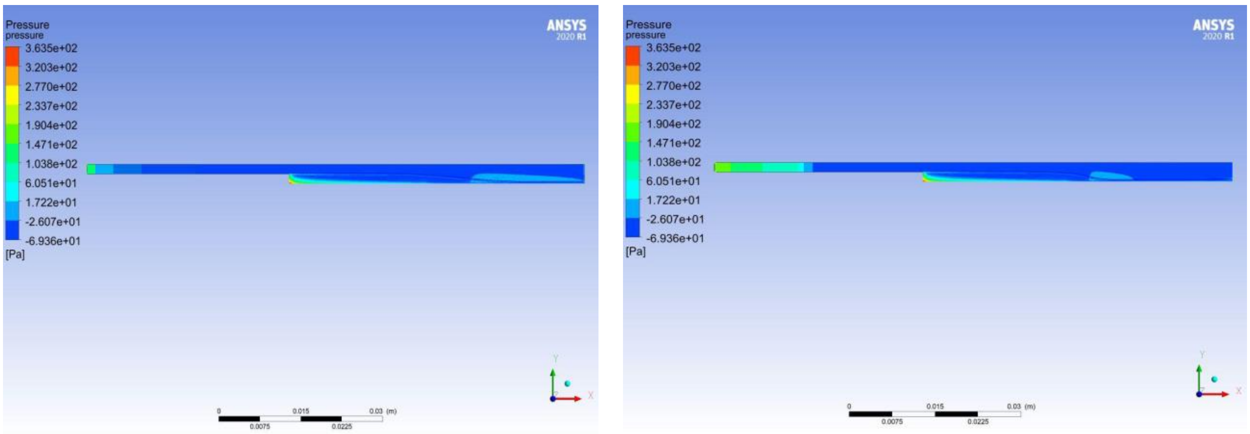
(a) (b)

Fig. 8. The velocity contour of (a) pure water, (b) 1% nanofluid (a) The velocity contour of pure water (b) The velocity contour of 1% nanofluid

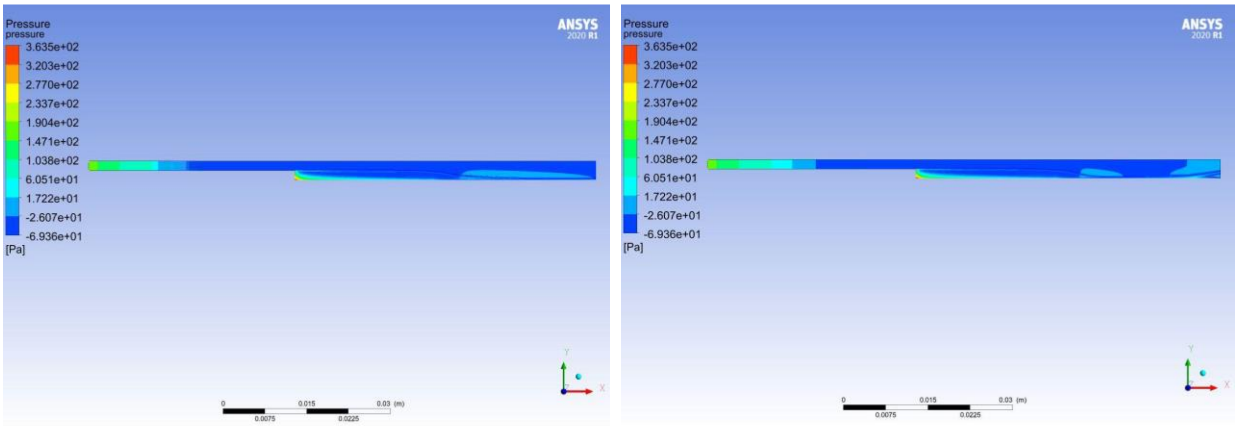
The pressure contours for (a) pure water, (b) 0.2% nanofluid, (c) 0.65% nanofluid, and (d) 1% nanofluid are displayed in Figure 9, respectively. When utilising nanofluid, as Figure 9 illustrates, the pressure distributions increase as the concentrations of nanoparticles increase because the higher viscosity of the fluid results in an increase in shear force.

As shown in Figure 10, the temperature contours correspond to the following: (a) pure water; (b) 0.2% nanofluid; (c) 0.65% nanofluid; and (d) 1% nanofluid. It demonstrates how the concentration of nanoparticles in the nanofluid is proportionate to its improved temperature distribution over pure water. Higher thermal conductivity of the nanofluid is the reason for this improvement. Quicker and more even temperature dispersion is the result of improved heat transmission caused by the fluid's nanoparticles.

These findings underscore the importance of nanoparticle characteristics in influencing heat transfer and fluid dynamics, with CFD analysis providing valuable insights for applications in various engineering contexts.

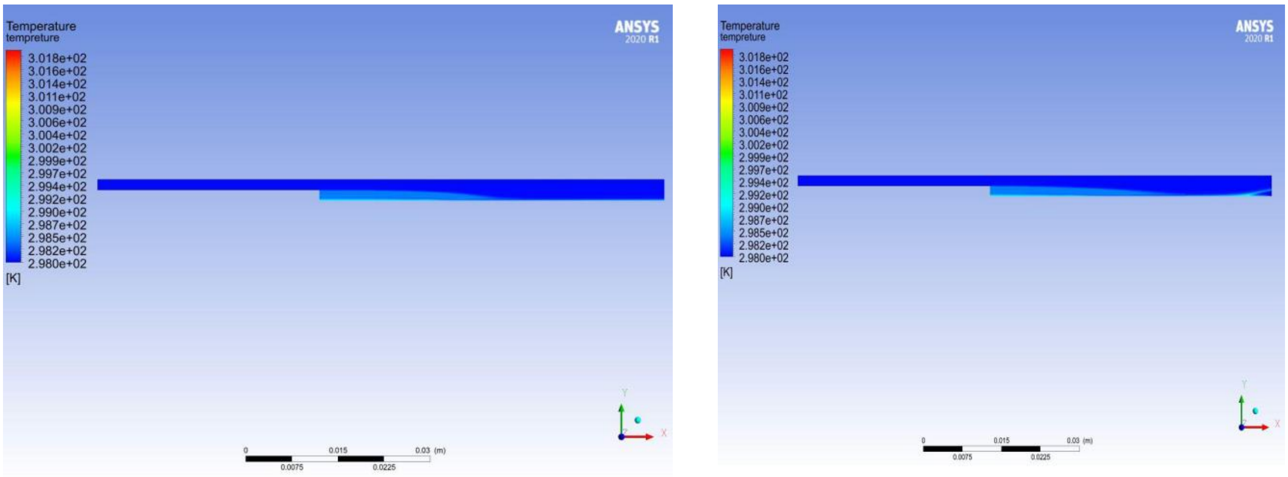


(a) (b)

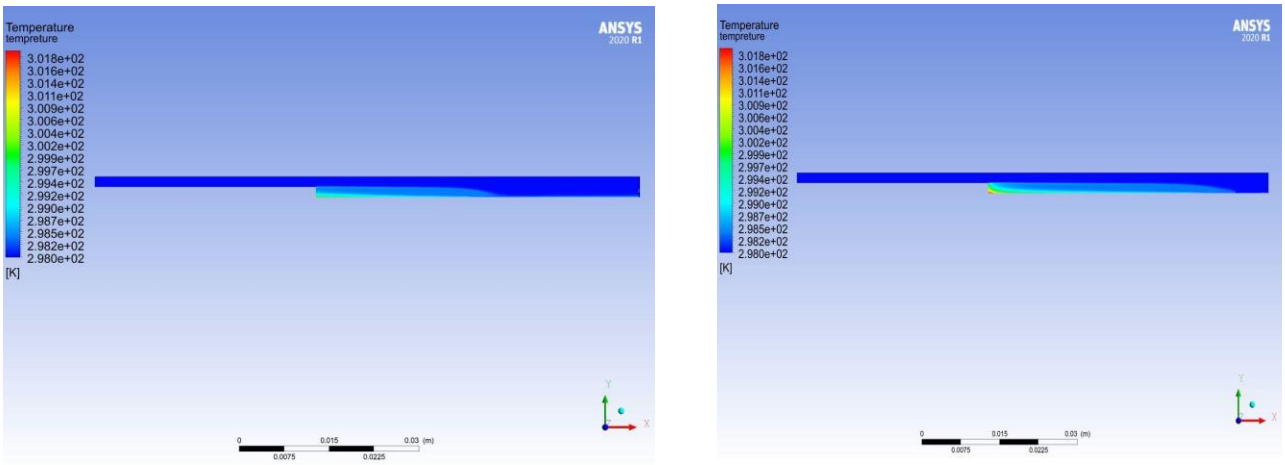


(c) (d)

Fig. 9. The pressure contour of (a) pure water, (b) 0.2% nanofluid, (c) 0.65% nanofluid, and (d) 1% nanofluid (a) The pressure contour of pure water (b) The pressure contour of 0.2% nanofluid (c) The pressure contour of 0.65% nanofluid (d) The pressure contour of 1% nanofluid



(a) (b)



(c) (d)

Fig. 10. The temperature contour of (a) pure water, (b) 0.2% nanofluid, (c) 0.65% nanofluid, and (d) 1% nanofluid (a) the temperature contour of pure water (b) the temperature contour of 0.2% nanofluid (c) the temperature contour of 0.65% nanofluid (d) the temperature contour of 1% nanofluid

5. Conclusions

The verification of heat transfer enhancement in a backward-going through step is vital for decreasing errors in the version equations and code. Three mesh sizes (0.2 mm, zero.15 mm, and zero.05 mm) had been hired to obtain the maximum accurate outcomes and check out distinct warmth switch areas. Mesh unbiased have a look at have been taken into consideration on this paper. The numerical investigation aimed to simulate laminar drift regimes over a step, in which the bottom wall become heated by a warmness flux. Various Reynolds numbers have been carried out inside the simulation starting from 200 to 900. In this simulation, carbon nanotube (CNT) with various extent fractions (zero.2%, 0.65% and 1%) had been investigated. The results tested an increase inside the average Nusselt wide variety with higher Reynolds numbers and nanoparticles' concentrations. Specifically, the 1% CNT nanofluid exhibited the highest increments in Nusselt quantity in comparison to the pure water.

The skin friction aspect reduced with increasing Reynolds number and decreasing nanoparticles' volume fraction. This emphasizes the advantages of the use of nanofluids for cooling applications. Nanofluids, characterized with the aid of their stronger thermal conductivity and heat transfer residences due to the presence of nanoparticles in a base fluid, offer big benefits in numerous cooling packages. The incorporation of nanoparticles, which include CNT, into the fluid now not simplest complements warmness dissipation but also improves the overall efficiency of cooling systems. These improvements have a right away impact on the performance, strength efficiency, and durability of cooling gadget, making nanofluids a promising solution inside the realm of thermal control. Moreover, the usage of nanofluids contributes to the development of sustainable and environmentally pleasant cooling technologies, aligning with the ongoing efforts to decorate strength conservation and reduce environmental impact.

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