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Determination of the Optimal Nanofluid Volume Fraction Range in an Evaporator Tube Using the Eulerian–Lagrangian Method

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Abstract

The addition of nanoparticles to a base fluid can enhance heat transfer; however, it also increases pressure drop, leading to higher pumping power and reduced economic efficiency. Therefore, identifying an optimal particle volume fraction is essential to ensure that the heat transfer enhancement outweighs the penalty of increased pressure drop. In this study, the optimal volume fraction range for several mono and hybrid nanoparticles was determined within a section of an evaporator tube using numerical simulations based on the Eulerian–Lagrangian approach. The Performance Evaluation Criterion (PEC) was employed as the main metric for performance assessment. The results showed that hybrid nanoparticles at volume fractions below 1% provide superior thermal performance compared to single-particle nanofluids. The optimal volume fraction ranges were found to be 0.01–0.2% for water–ethylene glycol/Co, 0.01–0.14% for water–ethylene glycol/CuO, 0.01–0.04% for water–ethylene glycol/Al₂O₃+TiO₂, and up to 0.03% for water–ethylene glycol/Al₂O₃. In contrast, water–ethylene glycol/SiO₂ consistently exhibited a PEC value below 1, indicating that its application in heat exchangers is not economically justified.

Keywords:

Evaporator, Eulerian-Lagrangian, Nanofluid, Efficiency, Pressure drop, Heat exchanger.

1. Introduction

Nanofluids have emerged as an effective method for enhancing heat transfer, primarily aimed at reducing the heat transfer surface area, material consumption, and energy requirements in heat exchanger manufacturing [1]. Despite their advantages, practical implementation faces several challenges. Accurate prediction of heat transfer coefficients and friction factors remains a critical issue. Determining thermophysical properties of nanofluids is complex [2], and stability limitations have further restricted their widespread use [3]. Experimental investigations are costly and time-consuming; therefore, numerical simulations provide a viable alternative for rapid and accurate evaluation, though validation against experimental or analytical solutions is essential.

Two main approaches are used for modeling nanofluid flows [4]. The single-phase model treats the mixture as a homogeneous fluid with effective properties, while the two-phase model considers the solid–liquid mixture behavior. Boertz et al. [5] used a single-phase SST $k-\omega$ model to simulate turbulent flow in a heated tube, showing increased Nusselt number alongside higher friction factor and pumping power. Saeed et al. [6] demonstrated that both temperature-dependent and independent property models could adequately predict laminar nanofluid flow. Uribe et al. [7] confirmed that heat transfer increases with nanoparticle volume fraction, while thermal boundary layer thickness decreases, suggesting two-phase models are not always required. Taskesen et al. [8] highlighted the effect of channel geometry, with circular cross-sections showing superior performance. Yildiz et al. [9] reported significant Nusselt number enhancement in turbulent flows using the $k-\epsilon$ model, though friction factor increased markedly. The need for further studies on thermophysical properties, considering experimental limitations, has been emphasized [10].

This study numerically investigates the effects of nanoparticle addition on pressure drop and heat transfer in an evaporator tube section. The nanofluid flows inside the tube while the surrounding refrigerant undergoes phase change. Key assumptions include: 1) the nanofluid flows in a straight evaporator tube with counter-current refrigerant, 2) the refrigerant is in evaporation with constant temperature and infinite specific heat, 3) nanoparticles are uniform in size and shape, moving at the base fluid velocity and in thermal equilibrium, 4) thermophysical properties are temperature-dependent and evaluated at bulk temperature, and 5) Reynolds number governs the flow.

This framework allows systematic evaluation of nanofluid performance in chiller applications, accounting for both heat transfer enhancement and the associated pressure drop, providing insights into optimal design conditions for efficient and

economically feasible heat exchangers.

2. Governing Equations

Continuity Equation

The conservation of mass is a fundamental principle in fluid mechanics. According to this principle, mass is neither created nor destroyed. For incompressible flows, this principle is expressed by the continuity equation, as given in Equation (1) [29].

$$\text{div}(\rho\vec{V}) = 0 \quad (1)$$

Momentum Equation

$$\rho \frac{\partial \vec{V}}{\partial t} + \text{div}(\rho\vec{V}\vec{V}) = -\text{grad}P + \mu(\nabla^2\vec{V}) + S_v \quad (2)$$

Energy Equation

$$\rho C_p \frac{\partial T}{\partial t} + \text{div}(\rho\vec{V}C_p T) = k(\nabla^2 T) + S_h \quad (3)$$

3. Results and Discussion

The study first simulated the base fluid, a 50/50 ethylene glycol/water (EG) mixture, without nanoparticles, and the pressure drop and heat transfer coefficient (h) were obtained for a Reynolds number of 4000. Subsequently, nanoparticles including Al_2O_3 , $\text{Al}_2\text{O}_3+\text{TiO}_2$, SiO_2 , Co , and CuO were added to the base fluid in volume fractions ranging from 0.1% to 0.4% to investigate their effects and determine the optimal concentration.

Figure 1 shows the pressure distribution along the tube for a 0.2% volume fraction of Al_2O_3 at $\text{Re} = 4000$. From this figure, it can be observed that the maximum pressure occurs at the tube inlet, approximately 1400 kPa, while the minimum pressure at the outlet is essentially zero. Figure 3 illustrates the particle trajectories along the tube as a function of pressure, providing insight into the flow behavior and particle movement within the nanofluid.

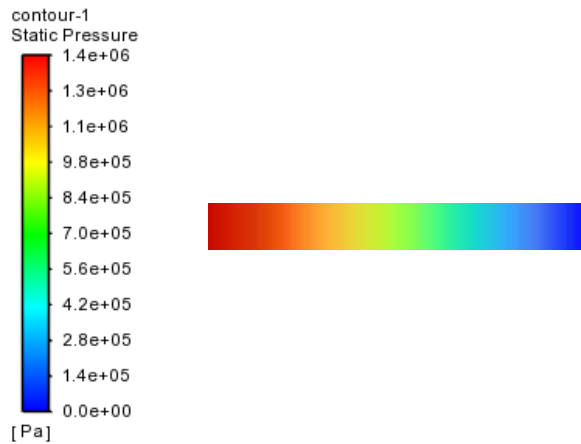


Figure 1. Pressure distribution along the x-direction for a 0.2% volume fraction of aluminum oxide at $\text{Re} = 4000$

Figure 2 shows the ratio of the nanofluid heat transfer coefficient to that of the base fluid ($h_{\text{nf}} / h_{\text{bf}}$) as a function of volume fraction for $\text{Re} = 4000$. For all nanoparticles, this ratio increases with increasing volume fraction. The increase is approximately similar for a volume fraction of 0.1%, but at higher volume fractions, a significant difference in the slope of h enhancement is observed, particularly for Al_2O_3 and $\text{Al}_2\text{O}_3+\text{TiO}_2$ nanoparticles.

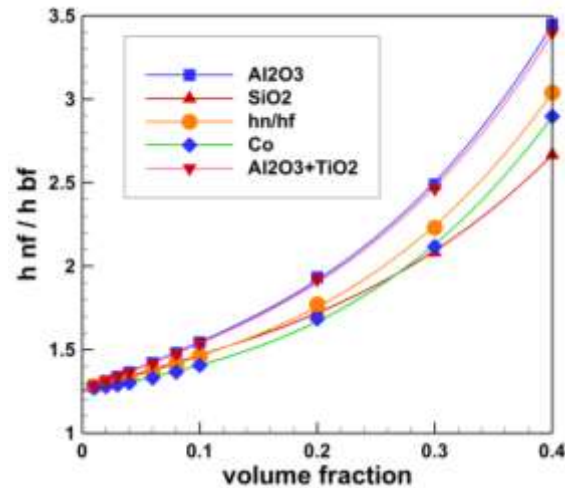


Figure 2. Ratio of the nanofluid heat transfer coefficient to that of the base fluid

Figure 3 shows the values of the performance factor (E) as a function of volume fraction for the five nanofluids studied at $Re = 4000$ (turbulent flow). For all selected nanofluids except water–ethylene glycol/SiO₂, the performance initially increases with volume fraction, reaches a maximum, and then decreases. For the water–ethylene glycol/Co nanofluid, the maximum performance occurs at a volume fraction of 0.3%, representing the highest efficiency among all nanoparticles considered. The next highest performance is observed for water–ethylene glycol/CuO, where the slope of performance enhancement with volume fraction is smaller, and the maximum performance is achieved within a narrow volume fraction range of 0.25% to 0.29%.

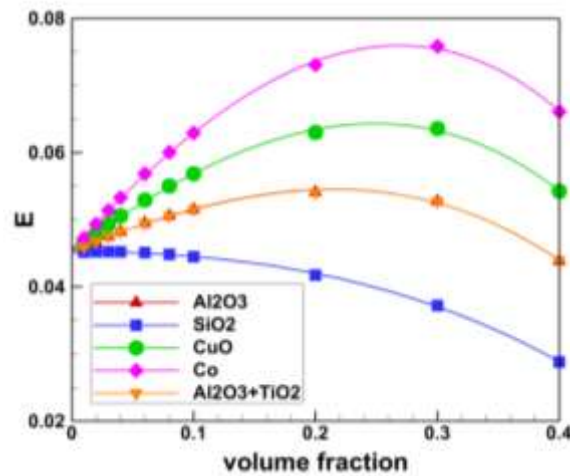


Figure 3. Evaporator performance (E) versus nanoparticle volume fraction at $Re = 4000$ for Al₂O₃, Al₂O₃+TiO₂, SiO₂, Co, and CuO nanoparticles

For the water–ethylene glycol/Al₂O₃ nanofluid, as shown in Figure 4, equations based on Fluent simulation data have been developed using an artificial neural network (ANN) in three stages: training, learning, and testing.

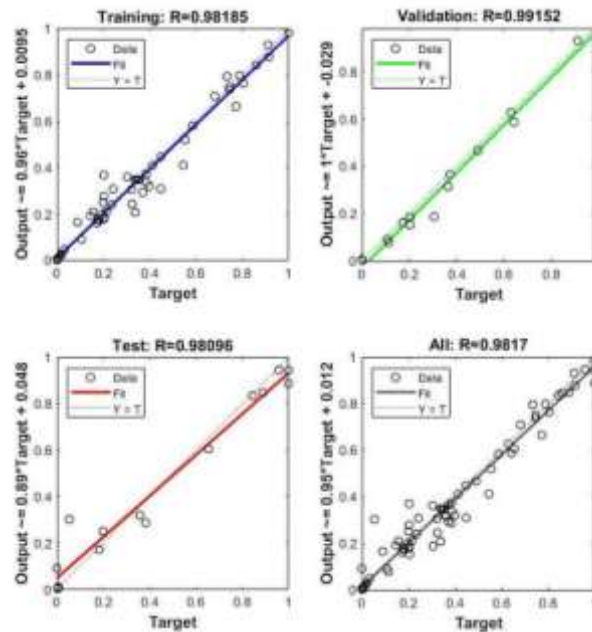


Figure 4. Training regression plot for the water–ethylene glycol/ Al_2O_3 nanofluid

4. Conclusion

Adding nanoparticles to a base fluid enhances heat transfer but increases pressure drop, raising pumping power and reducing economic feasibility. Identifying an optimal volume fraction is therefore essential, where heat transfer improvement outweighs the pressure penalty, as quantified by the Performance Evaluation Criterion (PEC). In this study, five nanoparticles— Al_2O_3 , $\text{Al}_2\text{O}_3+\text{TiO}_2$, SiO_2 , Co, and CuO—were tested in water–ethylene glycol. Hybrid $\text{Al}_2\text{O}_3+\text{TiO}_2$ showed superior performance below 1% volume fraction. Optimal ranges were 0.01–0.2% for Co, 0.01–0.14% for CuO, 0.01–0.04% for $\text{Al}_2\text{O}_3+\text{TiO}_2$, and up to 0.03% for Al_2O_3 . SiO_2 was not economical. Maximum PEC of 2.2 occurs for Co at 0.08% volume fraction and $\text{Re} = 4000$.

5. References

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