Thermo-Hydraulic Performance Enhancement of Liquid He Based Cryogenic Nanofluid Flow in Laminar Region Through Rectangular Plate Fin Heat Exchangers - A Numerical Study

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Abstract. Cryogenic applications are increasing in recent times with the advancement of technology. This research work is focused to improve performance of cryogenic fluid in compact heat exchangers. Nanoparticles with high thermal conductivity is mixed with the cryogenic fluid to improve the thermo-hydraulic efficiency of the heat transfer fluid used in the compact heat exchangers. Liquid He has been used as base fluid and its performance has been compared using nanoparticles CuO, Al2O3, Fe3O4 and Single Wall Carbon Nanotube (SWCNT). A numerical analysis has been done in the laminar range of flows in a PFHE. Comparison of the nanofluids at cryogenic temperature is compared with heat transfer performance parameter Colburn j-factor and pressure drop performance parameter Fanning’s friction factor (f). It has been found that around 15-30% enhancement of thermal performance is achieved with nanoparticles in comparison to liquid He without any nanoparticles. It has also been observed that there is an improvement of \( j/f^{1/3} \) factor representing heat transfer enhancement without much increasing pumping pressure.

1. Introduction
Liquefaction of gases, refrigeration, cryogenic energy storage systems, rocket and space applications are few examples where cryogenic fluids are used to exchange heat in compact heat exchangers. Plate Fin Heat Exchangers (PFHE) are very common in exchanging heat at cryogenic temperature. It is possible to save energy if performance of the PFHE can be increased or in other words waste heat can be reduced. Performance of the PFHEs depend on geometry of the fins, properties of the fluid and flow parameters (like mass flow rate). A lot of research work has been done on geometry of the fins to improve thermal performance. But in almost all the cases it has been observed that heat transfer enhancement occurs at the cost of high flow resistant passage which ultimately increases pumping power. Same conclusion can be made to increase the convective heat transfer coefficient by maintain high mass flow rate pumping power would be increased. The idea of nanofluid is improving the thermo-hydraulic efficiency of the PFHE by increasing the thermal conductivity of the fluid. Choi [1] first coined the term “nanofluids”, to refer dispersed nanoparticles (size less than 100 nm) into the base fluids. The common base fluids used were namely Water (W), oil, ethylene glycol (EG), W/EG based mixture are some of the common base fluids used for refrigeration purpose as reported by Redhwan et al. [2]. It was reported by Lee et al. [3] that nanofluids have higher thermal conductivity.
compared to their base fluids. They found that, Al₂O₃ nanoparticles of size 13 nm dispersed in water was increased by 30% of its thermal conductivity compared to water at 4.3% volume concentration.

PFHEs are very effective way of increasing rate of heat transfer because of very high area to volume ration. Most extensive experimental studies have been published by Kays and London [4]. It was reported that compact PFHEs of different fin shapes the pressure drop decrease in comparison with increasing the turbulence in the working fluid. provide Experimental findings of Norris and Spofford [5] reported the effect of the heat transfer coefficient and friction factor on the basis of thickness, length and pitch of the fins. Experimental studies by London and Shah [6] in 1967 concluded that a large number of fins per unit length and small offset spacing fin thickness gives better heat transfer. In1975 Wieting [7] proposed an empirical relation among the variables from earlier experiments to predict heat transfer and fluid flow friction for a PFHE of offset fin.

PFHEs performance also have been studied with cryogenic applications. Robertson [8] studied offset PFHE with subcooled liquid nitrogen at around 77K. Cao et al. [9] worked on PFHE with mixed refrigerant including CH₄, C₂H₆, C₆H₁₂, C₃H₈ and N₂ at about 113K. They found a large deviation in the heat transfer coefficient result from the existing correlations and experiments. A CFD simulation study done by Yang at al. [10] compared thermal performance of different cryogenic medium at gaseous and liquid state in OSF channels revealed that the fin materials with low thermal conductivity deteriorates the performance of the heat exchanger. Thermal performance of aluminum PFHEs were investigated with helium gas cooled to around 77K by Doohan et al. [11] and Goyal et al. [12]. Moreover, many cryogenic experiments were carried out to study the thermo-hydraulic performance of PFHE with helium gas at low temperature. One such report made by Wieting [13].

It has been noticed after literature survey that no work has been published comparing nanofluids performance applied in PFHE at cryogenic temperature with liquid He as base fluid. Liquid He and nanofluids with nanoparticles Al₂O₃, CuO, Fe₃O₄ and SWCNT of 5% volume fraction in each case are compared in terms of j-factor and f-factor and thermo hydraulic performance parameter $\frac{j}{f^{1/3}}$. In each nanofluids base fluid is considered as liquid He. A numerical simulation using Finite Volume Method (FVM) is used to analyze the thermo-hydraulic performance of the PFHE nanofluid at cryogenic temperature. Reynolds number range of the analysis has been set from 800 to 2000.

2. Numerical Analysis

2.1. Physical Description of the Model

The PFHE of rectangular cross section as shown in Fig 1 is of our interest of study for different ranges as mentioned below with liquid helium nanofluid as working fluid.

![Figure 1. Geometry of the Plain Rectangular PFHE](image-url)
2.2. Governing Equations
The governing equations to describe the fluid flow and heat transfer phenomena are continuity, momentum and energy equation. The mentioned equations are solved to get the velocity, pressure and temperature field. We have considered 3-D, turbulent and steady flow model, so the governing equations are as following,

Continuity equation:
\[ \nabla \cdot (\rho \mathbf{V}) = 0 \] (1)

Momentum equation:
\[ \nabla \cdot (\rho \mathbf{V} \mathbf{V}) = -\nabla P + \nabla \cdot (\mu \nabla \mathbf{V}) \] (2)

Energy equation:
\[ \nabla \cdot (\rho c_p \mathbf{V} T) = \nabla \cdot (k \nabla T) \] (3)

2.3. Thermophysical Properties of the Nanofluids
By applying the principle of mass conservation to the two species in finite control volume of the nanofluids, the nanofluid density was obtained from the relation:
\[ \rho_{nf} = \rho_{np} + (1 - \varphi) \] (4)

By applying the principle of calorimetry in the mixture the overall specific heat of the nanofluid was calculated from the relation:
\[ c_{nf} = \frac{\varphi \rho_{np} c_p + (1 - \varphi) \rho_{b} c_p}{\varphi \rho_{np} + (1 - \varphi) \rho_{b}} \] (5)

Maxwell model of equivalent thermal conductivity as studied by Yu et al. [14] was used for the estimation of the thermal conductivity and the Einstein model of viscosity as mentioned by Mishra et al. [15] were used to estimate the viscosity of the nanofluid.
\[ \mu_{nf} = \mu_b (1 + 2.5\varphi) \] (6)
\[ k_{nf} = k_b \frac{k_{np} + 2k_b + 2\varphi(k_{np} - k_b)}{k_{np} + 2k_b - \varphi(k_{np} - k_b)} \] (7)

2.4. Boundary Conditions
The inlet, outlet and wall boundary conditions are as shown in Figure 2. Top, bottom and periodic side walls are assumed to be no slip boundary condition. Sidewall is kept at periodic boundary condition and bottom and top wall is kept at constant temperature boundary condition. Inlet set as velocity inlet boundary condition corresponding to the Re range from 800 to 2000 to assure the flow is laminar.

| Table 1. Geometry of the Plain Rectangular PFHE |
| --- | --- |
| Parameters | Working range |
| Reynolds number | \( 800 \leq Re \leq 2000 \) |
| Volume fraction of nanoparticles | \( \varphi = 5\% \) |
| Height of the fin | \( h = 9.75[\text{mm}] \) |
| Fin spacing | \( s = 4.85[\text{mm}] \) |
| Thickness of the fin | \( t = 0.25[\text{mm}] \) |
| Length of the fin | \( 100[\text{mm}] \) |
2.5. Meshing and Model Setup
The mesh of the computational domain was generated using a triangular patch conforming method. This mesh contains hexahedral cells having rectangular faces at the boundaries. The generated mesh consisted of 233460 elements and 245063 nodes.

A 3-D, incompressible and pressure-based solver was chosen for the computational domain. A laminar viscous model is used for numerical simulation. A 2nd order upwind interpolation formula was used for discretization of momentum and energy equation. The conventional SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) algorithm was used to solve the pressure velocity coupled equations, where several iterations were performed to ensure convergence of the numerical solution was assured by monitoring the scaled residuals to a constant level of $10^{-6}$ for each variable.

2.6. Grid Independence
The solution obtained in this work is mesh independent as we have studied the mesh independency test. The result is shown in Figure 3.

![Grid Independence Test](image)

**Figure 3. Grid Independence Test**
2.7. Experimental Validation of the Model
Validation is done to check the authenticity of the CFD tool. We have validated the model by comparing the results of the experiment done by Kays and London [4] as shown in Figure 4.

![Figure 4. Validation of simulation result with the experiment of Kays and London [4]](image)

3. Results and Discussion
This is clear from the solution of the numerical analysis as shown in Figure 5 and Figure 6 that with the increase of Re in the laminar region from 800 to 2000 friction factor and j factor decreases. These variation of f and j with Re is similar in both cryogenic nanofluids and pure liquid He. Friction factor is a non-dimensional term used to calculate the pressure drop in the PFHE. On the other hand, Colburn j factor is a non-dimensional term used to estimate the heat transfer coefficient and hence the effectiveness of the PFHE.

![Figure 5. Comparison of friction factors among different nano-particles with liquid He](image)
It is observed in Figure 6 that CuO nanoparticles are very effective in increasing the convective heat transfer coefficient in terms of Colburn j-factor in comparison to Al₂O₃, Fe₃O₄ and SWCNT. But pressure drop in terms of Fanning’s friction factor is also high in case of CuO-liquid He cryo-nanofluid in comparison to other cryo-nanofluids as shown in Figure 5. But this is quite clear from the Figure 5 and Figure 6 that in comparison to liquid He only, He based cryo-nanofluids are more effective in terms of convective heat transfer.

This is very important to conclude regarding the performance of the PFHE keeping in mind both the heat exchange and pressure drop in the device. That is why volume goodness factor, defined as $j/f^{1/3}$, is compared among the different cryo-nanofluids as shown in Figure 7. It is observed that CuO

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**Figure 6.** Comparison of Colburn j factor among different nano-particles with liquid He

**Figure 7.** Comparison of volume goodness factor among different among different nano-particles with liquid He
nanofluids are giving better overall performance in terms of volume goodness factor in comparison to other cryo-nanofluids. Overall performance enhancement in He based cryo-nanofluids is around 25% to 30% in comparison to only liquid He, is clearly observed in Figure 7.

4. Conclusion
In this research work performance of PFHE with one fluid as He based cryo-nanofluid is compared with respect to liquid He at laminar range. It can be concluded from the results that CuO-liq. He based cryo-nanofluid having best performance among the other cryo-nanofluids studied based on volume goodness factor. Around 25% to 30% enhancement in the overall performance considering both heat exchange and pressure drop has been found when cryo-nanofluids are used in comparison to liquid He only. But in this research certain aspects like cost of nano-particles, preparation complexity and cost of cryo-nanofluid, phase change stability of nanofluids have not been considered in evaluation of overall performance of the PFHE.

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