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A Comparative Study and Analysis of Shell and Tube Heat Exchanger Using Nanofluid

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Abstract: This paper explores the effects of nanofluid, namely Aluminium Oxide (Al_2O_3), Titanium Oxide (TiO_2), and Magnesium Oxide (MgO) as working fluids in a compact shell and tube heat exchanger. The study focuses on assessing Thermal efficiency, namely Heat transfer coefficient and Nusselt number, under different conditions. Nanofluid is used on the tube side as cold fluid, while water serves as the hot fluid on the shell side. Parameters such as nanofluid concentration (0.8%, 1.5%, and 2% by volume) and inlet flow velocity of cold fluid (0.4 m/s, 0.7 m/s and 1 m/s) are varied. Study uses a single-pass, counter-flow heat exchanger, modelled using ANSYS Fluent for CFD simulation. This research explores the change in heat transfer with varying velocity and concentration and also studies the potential of compact heat exchangers, which are increasingly preferred for their efficiency and space-saving design.

Keywords*:* CFD, Heat Transfer Coefficient, Nusselt Number, Flow Velocity, Nanofluid, Shell & Tube Heat Exchanger (STHE).

I. INTRODUCTION

Shell and tube heat exchanger (STHE) is a device that facilitates the transfer of heat between two fluids, typically liquid or gas, without having a direct contact. This design is most widely used heat exchangers, particularly in high-pressure applications such as petroleum refineries and large chemical processes [1].

A comparative study and analysis of (STHEs) utilizing nanofluid examines the integration of heat transfer fluids to enhance thermal efficiency in various industrial applications. STHEs are employed in sectors such as power generation, chemical industry, and refrigeration for their robust design and effective heat exchange capabilities between two fluids. Recent research has highlighted the use of nanoparticles in a base fluid as a promising approach to improve the thermal performance of these heat exchangers, leading to reduced energy consumption and improved operational efficiency [2].

The notable advantage of using nanofluids lies in their thermal properties, which gives better heat transfer and reduced size requirements for heat exchangers. Studies have demonstrated that the addition of nanoparticles, such as aluminium oxide (Al2O3) and copper (Cu), can significantly increase heat transfer rates, with improvements reported as high as 103.07% in certain configurations. However, the introduction of nanofluid comes with challenges; increased pressure drops and sedimentation issues can complicate their practical application and impact overall system efficiency [3].

Controversies surrounding the application of nanofluid in STHEs primarily revolve around the balance between enhanced thermal performance and increased operational complexities, including the costs of nanofluid production and maintenance. While some studies emphasize the energy-saving potential of nanofluid, others raise concerns about their long-term stability and the implications for industrial scalability. Ongoing research in this field helps to address these challenges by optimizing preparation methods, improving measurement techniques, and exploring hybrid nanofluid to maximize performance.

A lot of research is dedicated to the studying of the performance of heat exchangers using nanofluids. One of the research studies the thermal efficiency of a STHE using nanofluids (ZnO, CuO, Fe_3O_4, TiO_2, and Al_2O_3) in water at 0.03% volume concentration was done by comparing their heat transfer efficiency and energy effectiveness with base fluid as water. Al_2O_3-W nanofluid showed the best result. ZnO-W nanofluid improved energy effectiveness by 43%, while Al_2O_3-W nanofluid had the lowest (31%) I. M. Shahrul et al. [4]. Mohammed Abbood et al. [5] assess the performance of Al_2O_3 nanofluid at 2% concentration. The result showed a notable improvement in outlet water temperature by 11.23% compared to traditional hot water approach. V. Rambabu et al. [6] investigated the heat transfer of TiO_2-watrer nanofluid in a STHE under turbulent flow, comparing with water as the base fluid. The performance improved at varying

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concentrations (0.05%–0.2%) and flow rates. Compared to water the addition of nanoparticles increased overall heat transfer, Reynolds number, and effectiveness. M. Manikanta et al. [7] conducted an experiment by varying nanoparticle (MgO) volume concentration (0.1%, 0.3% and 0.5%) and flow rates to evaluate parameters like thermal conductivity, heat transfer coefficient, and Nusselt number. The study recorded an enhancement of 37.71% in the overall heat transfer with 0.5% MgO nanofluid at specific flow rates. Also, the thermal conductivity and Nusselt number improved with concentration and temperature. Mehmet Senan Yilmaz et al. [8] replace macro tubes with mini channels in STHE and studied the performance of Al_2O_3-water nanofluid with six volume concentrations (0.02%, 0.1%, 0.2%, 0.4%, 0.6%, and 0.8%) on heat transfer and pressure drop.

Kolukula Satish et al. [9] studied the overall heat transfer, effectiveness and friction factor of two nanofluid namely Al_2O_3 and SiO_2 based on concentration and flow velocity. Al_2O_3 heat transfer performance showed better result compared to SiO_2.

From the available literature, it was found that heat transfer performance evaluation is mainly done based on changing concentration and mass flow rates of nanofluids. However, there are limited studies where the performance is studied by varying the inlet velocity of both cold fluid side and hot fluid side of STHE.

Therefore, in this research, the performance of a compact STHE is studied by varying the nanofluid concentration and cold side flow velocity through which the nanofluid is flowing. Also, a comparative study between Al_2O_3, TiO_2 and MgO is done to check how the variation affects various nanofluids.

II. METHODOLOGY

This section explores the use of three nanofluids, namely aluminium oxide, titanium oxide and Magnesium oxide, based on concentration and flow velocity for improving the heat transfer in the STHE and drawing a comparison among the three. A detailed CFD simulation is carried out to find the optimal solution using Ansys Fluent based on the parameters mentioned.

A. Basic Heat Transfer Fundamentals

Heat transfer occurs when there is a difference in temperature in a medium or between media. It naturally takes place from areas of high temperature to areas of low temperature and is basic requirement in thermodynamics, engineering and physics.
There are mainly 3 modes of heat transfer, namely conduction, convection, and radiation.

1) Conduction:
In conduction, the transfer of heat occurs through direct interaction without the movement of material. The equation is given below [5].

$$q = -k\nabla T \quad [1]$$

Where q'' is the heat flux, k is thermal conductivity, and ∇T is temperature gradient.

2) Convection:
When heat transfer involves movement of heat through fluid (liquid or gas) caused by bulk movement of the fluid [5].

$$q'' = h\,(T_s - T_\infty) \quad [2]$$

Where h is convection heat transfer coefficient, T_S is surface temperature, and T_∞ is the ambient temperature.

3) Radiation:
Radiation is the transfer of heat through electromagnetic waves without requiring an actual medium. It also occurs in a vacuum, unlike conduction and convection, which require a medium to transfer [5].

$$q'' = \epsilon\sigma Ts4 \quad [3]$$

B. Heat Exchanger

1) Overview:

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Heat exchangers are devices that transfer heat efficiently between fluids without actually mixing them (Figure 1), commonly have their application in power plants, automobiles, HVAC systems, etc. Common types include shell and tube, plate, air-cooled, and double pipe heat exchangers. The flow patterns include counter flow, parallel flow, or cross flow to maximize efficiency based on various applications. Modern advancements, like using nanofluid, a fluid enhanced with nano particles that improves heat transfer by improving thermal conductivity. The theoretical heat exchanger equations used are shown in the subsequent headings.

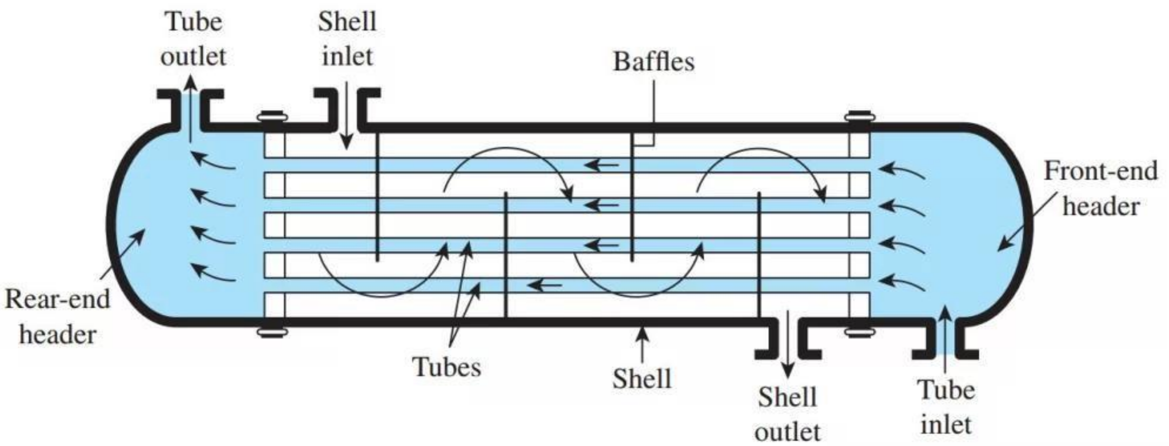

Figure.1 Shell and Tube Heat Exchanger (Source: PetroSync Blog)

2) *Continuity equation (Mass conservation):*

$$\partial \rho/\partial t+\nabla\cdot (\rho.u) =0 \qquad [4]$$

Where ρ is the fluid density, t is time, u is the velocity vector, and *div(ρu)* is the divergence of the mass flux [5].

3) *Momentum equation (Navier-Stokes equations):*
Govern the motion of fluid due to forces (pressure, viscous, and turbulent stresses) Equations (for each direction x, y, z):

$$\partial(pu)/\partial t+\nabla\cdot(\rho uu)=-\partial p/\partial x+\nabla\cdot(\mu\nabla u)+S_x \qquad [5]$$

$$\partial(pv)/\partial t+\nabla\cdot(\rho uv)=-\partial p/\partial x+\nabla\cdot(\mu\nabla v)+S_y \qquad [6]$$

$$\partial(pw)/\partial t+\nabla\cdot(\rho uw)=-\partial p/\partial x+\nabla\cdot(\mu\nabla w)+S_z \qquad [7]$$

Where p is the pressure, μ is the dynamic viscosity, and $u\times\nabla u$ represents the convection term and Sx is the external forces acting on the fluid element in the x-direction. Similarly, y and z direction the formulas are given. [5].

4) *Energy equation (Heat transfer)***:**

$$\partial(\rho E)/\partial t+\nabla\cdot[v(\rho E+p)]=\nabla\cdot(k_{eff}\nabla T)+SE \qquad (8)$$

Here E is the total energy (Internal & Kinetic), K_{eff} is the effective thermal conductivity, T is temperature, and SE is the enthalpy at source or sink [5].

C. Nanofluid Selection

For the study, three nanoparticles, namely Aluminium Oxide, Titanium Oxide and Magnesium Oxide are selected. Among this three Aluminium Oxide is most widely used in heat transfer applications because it is readily available and cost-effective compared to the other two nanoparticles. Whereas Magnesium Oxide has the highest thermal conductivity, but is less common due to higher production cost, and is used for specialized applications. Also, titanium Oxide is chemically stable in corrosive environments. Here, the properties of the nanofluid particle and equations were taken from references [4, 10 and 11].

TABLE I PROPERTIES OF NANOPARTICLES & BASE FLUID

Properties	Aluminium Oxide (Al_2O_3)	Titanium Oxide (TiO_2)	Magnesium Oxide (MgO)	Water (H_2O)
Thermal Conductivity (λ) (W/m K)	40	11.7	60	0.6
Specific Heat (C_p) (J/Kg K)	955	697	1030	4183
Density (ρ) (Kg/m^3)	3900	4260	3580	997
Viscosity (μ) (Kg/m.s)	-	-	-	8.94 10^{-4}

D. Analytical Formula for calculating Nano fluid properties

1) *Thermal Conductivity (λ_{nf}):*

$$\lambda_{nf} = [\lambda_{np} + 2\lambda_{bf} + 2(\lambda_{np} - \lambda_{bf})\,\phi * \lambda_{bf}] / [\lambda_{np} + 2\,\lambda_{bf} - (\lambda_{np} - \lambda_{bf})\,\phi] \quad [9]$$

2) *Specific Heat (C_{np}):*

$$C_{nf} = [(\phi\, \rho_{np}\, C_{Pnp}) + (1 - \phi)\, \rho_{bf} C_{Pbf}] / [\phi\, \rho_{np} + (1 - \phi)\, \rho_{bf}] \quad [10]$$

3) *Density (ρ_{nf}):*

$$\rho_{nf} = \rho_{np}\phi + \rho_{bf}(1 - \phi) \quad [11]$$

4) *Viscosity (μ_{nf}):*

$$\mu_{nf} = \mu_{bf}\,(1 + 2.5\phi) \quad [12]$$

Where,

λ_{nf} = Thermal conductivity of Nano fluid μ_{nf} = Viscosity of Nano fluid λ_{np} = Thermal conductivity of Nano particle μ_{bf} = Viscosity of Base fluid λ_{bf} = Thermal conductivity of Base fluid Φ = volume fraction of Nano particles ρ_{nf} = Density of Nano fluid ρ_{np} = Density of Nano particle ρ_{bf} = Density of Base fluid CP_{nf} = Specific heat of Nano fluid CP_{np} =Specific heat of Nano particle CP_{bf} = Specific heat of Base fluid

E. Design Specification of Heat Exchanger

The dimensions is referenced from the heat exchanger Model HE 668 by SOLTEQ which is used for engineering and research purpose. The CAD design has been done in Solidwork Software (Figure 2).

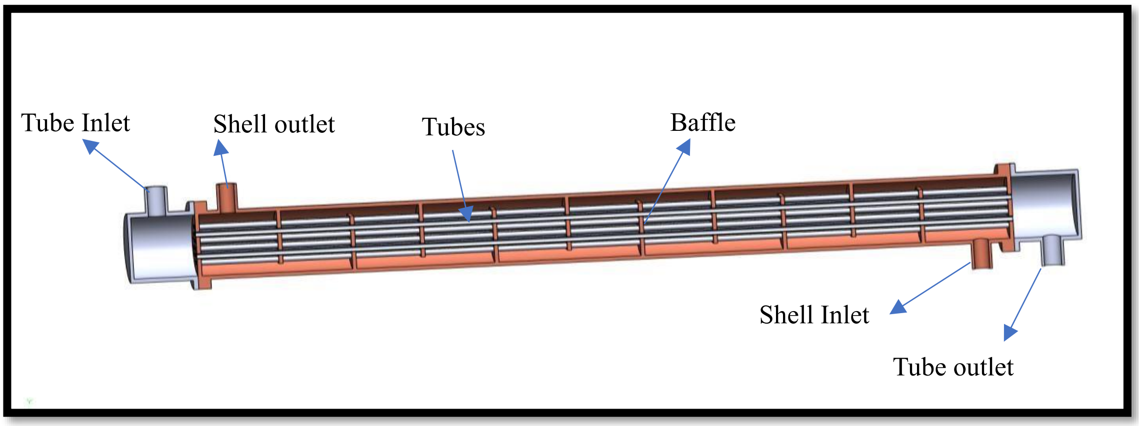

Figure 2. Cross-Sectional View of the Heat Exchanger

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1) Shell Dimensions:
- Length (L) = 1900 mm
- Outer Diameter (D_o)= 172 mm
- Inner Diameter (D_i) = 154 mm
- Baffle Spacing (B) = 130 mm
- Number of Baffle (n_b) = 10 Baffle Cut = 30%
- Baffle Thickness (t_b) = 8 mm

2) Tube Dimensions:
- Length (l) = 1630 mm
- Outer Diameter (do) = 13 mm
- Inner Diameter (di) = 10 mm
- Number of Tubes (n) = 30
- Tube Arrangement = Triangular Tube Pitch (Pt) = 20 mm

3) Other Specifications:
- Single Pass
- Shell Side Velocity = 0.5 m/s
- Flow Type = Counter Flow
- Tube Inlet Temperature = 30 oC Shell Inlet Temperature = 80 oC

TABLE II PROPERTIES OF NANO-FLUID (WATER & NANOPARTICLE) BASED ON CONCENTRATION

Aluminium Oxide (Al_2O_3)				
Concentration (ϕ)	Thermal Conductivity (λ_{nf}) (W/m K)	Specific Heat (C_p) (J/Kg K)	Density (ρ_{nf}) (Kg/m3)	Viscosity (μ_{nf}) (Kg/m s)
0.8	1.0169	4084.283	1020.224	0.000912
1.5	1.0320	4001.520	1040.545	0.000927
2.0	1.0429	3944.356	1055.060	0.000939
Titanium Oxide (TiO_2)				
Concentration (ϕ)	Thermal Conductivity (λ_{nf}) (W/m K)	Specific Heat (C_p) (J/Kg K)	Density (ρ_{nf}) (Kg/m^3)	Viscosity (μ_{nf}) (Kg/m s)
0.8	1.0150	4066.880	1023.104	0.000912
1.5	1.0288	3970.030	1045.945	0.000927
2.0	1.0385	3903.401	1062.260	0.000939
Magnesium Oxide (MgO)				
Concentration (ϕ)	Thermal Conductivity (λ_{nf}) (W/m K)	Specific Heat (C_p) (J/Kg K)	Density (ρ_{nf}) (Kg/m3)	Viscosity (μ_{nf}) (Kg/m s)
0.8	1.0172	4094.265	1017.664	0.000912
1.5	1.0325	4019.527	1035.745	0.000927
2.0	1.0435	3967.721	1048.660	0.000939

The data provided in table 2 includes properties of nanofluid based on changing concentration are utilised in Ansys material section for simulation. Also, the data for inlet velocities (0.4m/s, 0.7m/s and 1m/s)[9] and temperatures for tube side[12] and shell side[13] are computed in the inlet condition of the simulation. The mesh obtained as shown in Fig. 3 has 6937221 elements for the whole domain. Also other settings are shown in table 3.

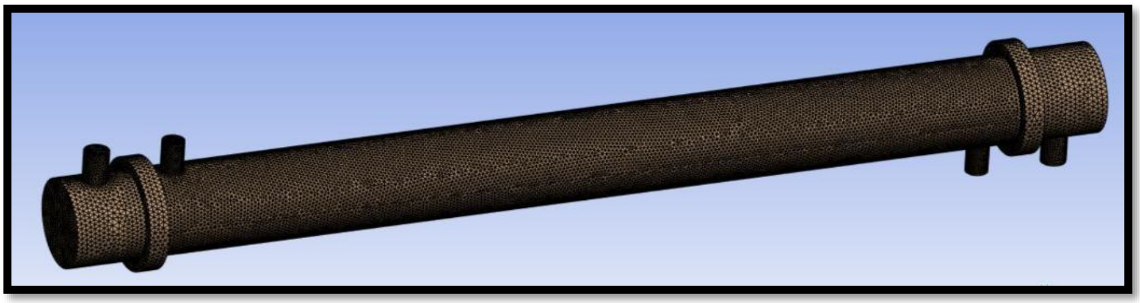

Figure 3. Mesh Result of Heat Exchanger

TABLE III MESH SETTINGS

Element Size	50 mm
Minimum Curvature Size	03 mm
Total Number of Nodes	1398155
Total Elements	6937221
Smoothing	Medium
Element Order	Linear
Total Simulation	27

In Ansys Fluent the pressure based steady state solver is used. The energy equation is important for heat transfer simulations, without it fluent cannot compute the temperature variations between the hot and cold fluids.
The model selected is k-epsilon model (2-Equation) where k represent the intensity of turbulence and ϵ (Epsilon) represents the turbulent dissipation rate.
Also the k-epsilon realizable model was used which is an upgraded version of k-epsilon model. Ideal for the shell-side, where flow ciruclating the baffles and across tubes introduces complex turbulence.
Lastly, scalable wall functions is used for the purpose of near wall turbulence without requiring a highly refined mesh near the walls.

F. Analytical Formula for calculation of heat transfer performance

1) Heat Transfer Rate (Q):

$$Q = \dot{m}_t C_p \, (T_{inlet} - T_{outlet}) \quad [13]$$

Where,

$\dot{m}_t = \rho Av$ is mass flow rate at cold fluid side.
ρ is nanofluid density A is tube area v is cold side inlet velocity
T_{inlet} and T_{outlet} are inlet and outlet temperature at tube side

2) Heat Transfer Coefficient (h_t):

$$H = Q \,/\, A.\ \Delta T_m \quad [14]$$

Where,
Q is heat transfer rates
A is heat transfer area of tube
ΔT_m is log mean transfer difference (LMTD)

3) Nusselt Number (N_u)

$$N_u = h_t D_{h\,/} K_{nf} \qquad E \quad [15]$$

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Where,

h_t is heat transfer coefficient D_h is Hydraulic diameter (d_{inner}) K_{nf} is thermal conductivity

III. RESULTS AND DISCUSSION

In this section the results obtained is shown and a comparison between the nanofluids is studied based on nanofluid concentration and inlet flow velocity. Also, a comparison is done among temperature contours datasets obtained from CFD simulation.

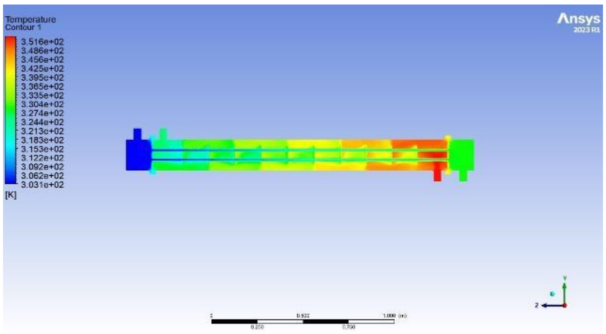

Figure 4. Temperature contour of Al_2O_3 at 0.8% concentration at 0.4m/s

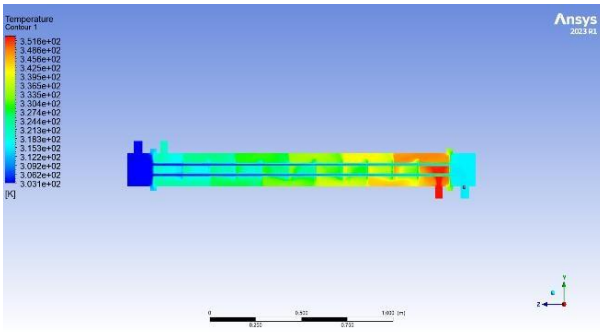

Figure 5. Temperature contour of Al_2O_3 at 0.8% concentration at 1m/s

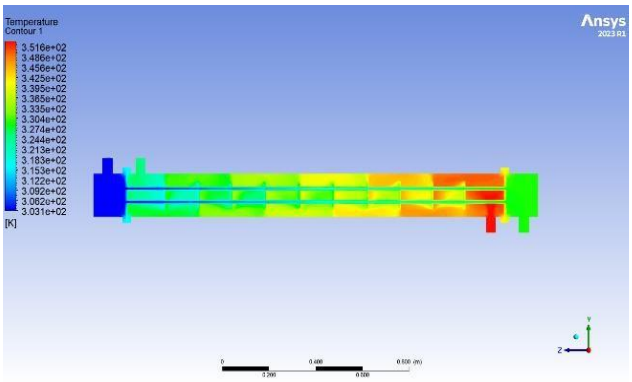

Figure 6. Temperature contour of Al_2O_3 at 2.0% concentration at 0.4m/s

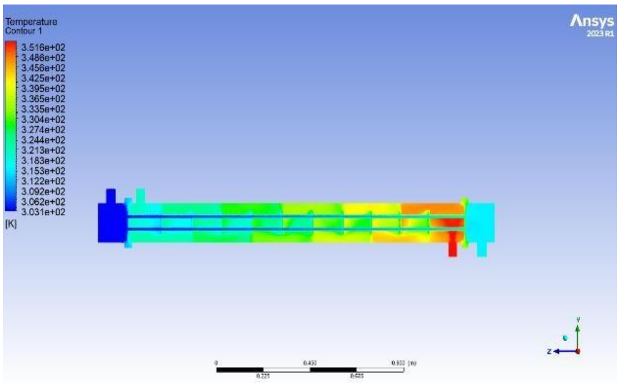

Figure 7. Temperature contour of Al_2O_3 at 2.0% concentration at 1m/s

The temperature contour of Al_2O_3 with changing nanofluid concentration and cold inlet velocity is depicted in figures 47 shows clear improvement in heat transfer performance. Fig.4 has high a localised temperature region indicating low concentration and flow velocity. Fig 5-6 shows a moderate to even temperature gradient, suggesting significant improvement in heat transfer. Lastly, Fig.4 exhibits most the uniform and widespread temperature distribution.

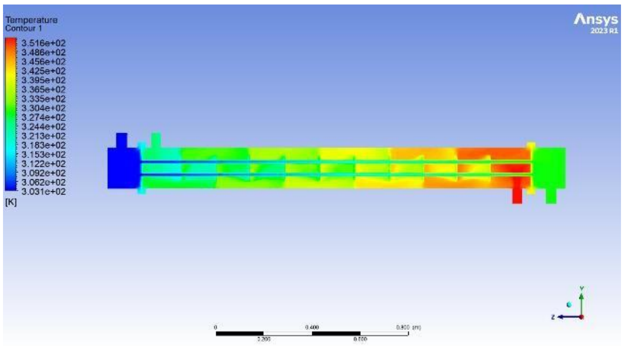

Figure 8. Temperature contour of MgO at 0.8% concentration at 0.4m/s

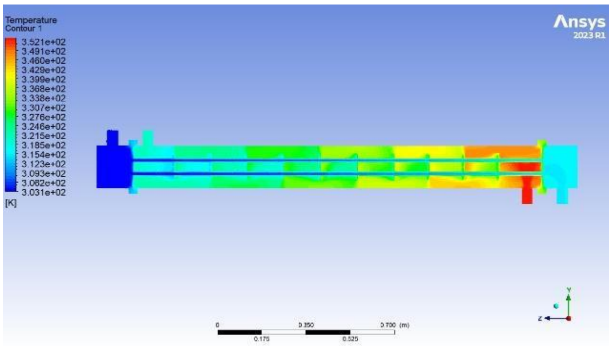

Figure 9. Temperature contour of MgO at 0.8% concentration at 1m/s

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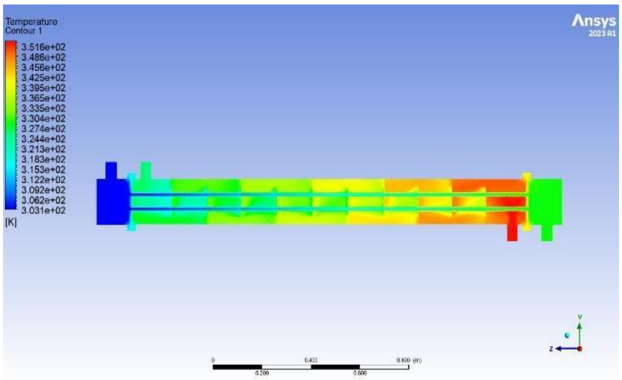

Figure 10. Temperature contour of MgO at 2.0% concentration at 0.4m/s

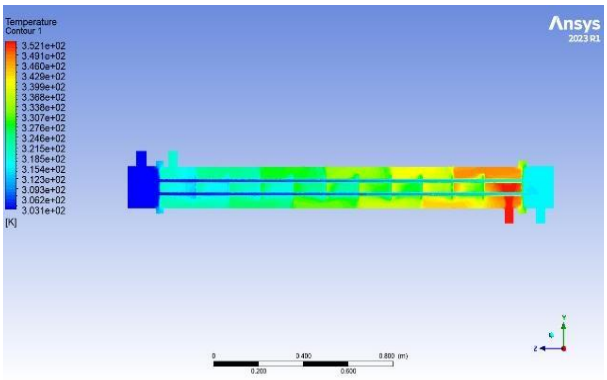

Figure 11. Temperature contour of MgO at 2.0% concentration at 1m/s

Fig. 8-11 shows the contour of MgO with changing concentration and velocity. As seen in Fig. 9 the contour is better in comparison to the contour in Fig. 8 (dark blue to green and then light blue on the tube area and then in shell area red to green and then light blue color) suggesting that at higher velocity the heat transfer performance increases but the effect is prominent in contour shown in fig.11 which is also due to higher concentration of nanofluid.

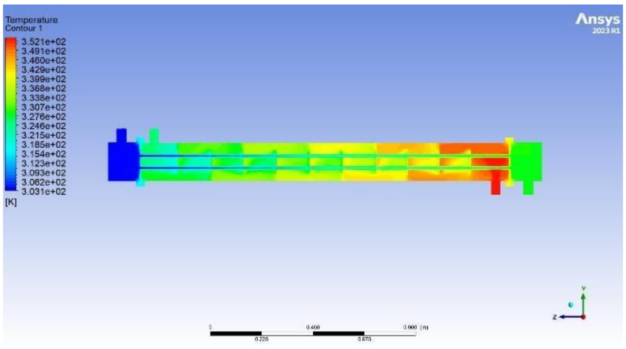

Figure 12. Temperature contour of TiO_2 at 0.8% concentration at 0.4m/s

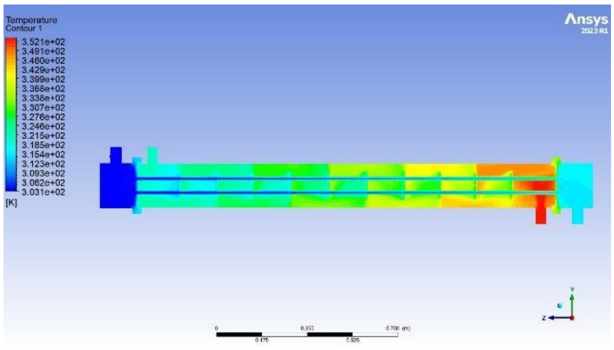

Figure 13. Temperature contour of TiO_2 at 0.8% concentration at 1m/s

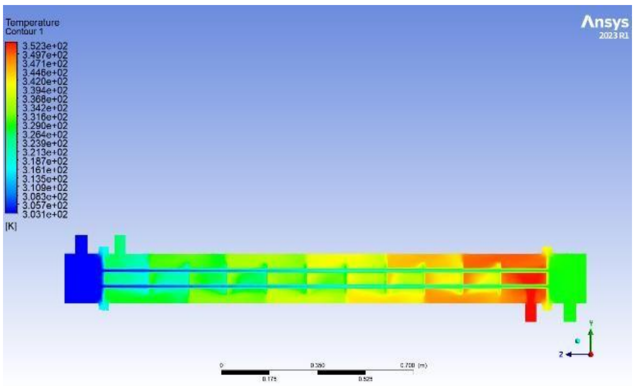

Figure 14. Temperature contour of TiO_2 at 2.0% concentration at 0.4m/s

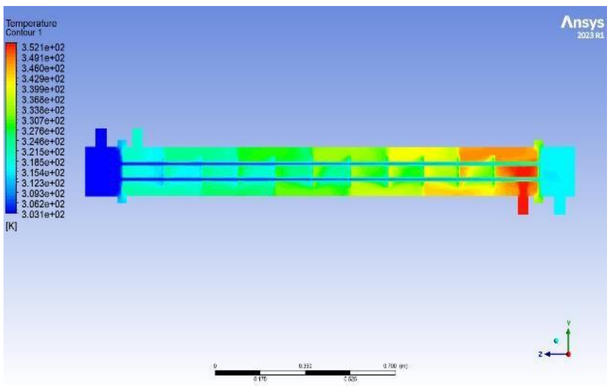

Figure 15. Temperature contour of TiO_2 at 2.0% concentration at 1m/s

Similarly, in the case of TiO_2 also the improvement in heat transfer increases as concentration and velocity increases as can be seen in Fig. 12-15. TiO_2 at 2% conc. and 1m/s velocity shows better performance compared to the other three contours. Among these three nanofluid temperature contour Al_2O_3, shows better performance values it has higher thermal conductivity and specific heat with increased concentration.
Data obtained from the simulation study are plotted between heat transfer coefficient and nanofluid inlet velocity; and Nusselt number and nanofluid Inlet velocity for the three nanofluids (Fig.4-9).

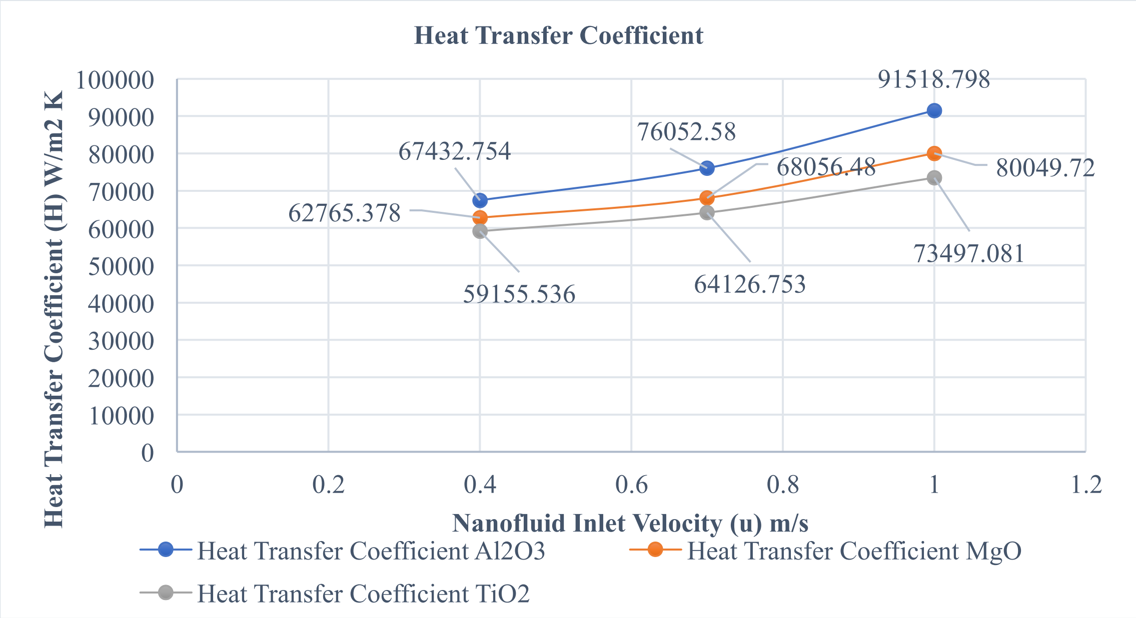

Figure.16 Heat Transfer Coefficient between Al_2O_3, TiO_2 and MgO at 0.8% concentration

The percentage change in heat transfer coefficient of Al_2O_3 from 0.4m/s to 0.7m/s at 0.8% concentration is 12.78% and 20.34% from 0.7m/s to 1m/s inlet velocity. Whereas the percentage change in heat transfer coefficient of TiO_2 are 8.4% and 14.61% respectively. Similarly, the values of MgO are 8.43% and 17.62% for the two inlet velocity difference at 0.8% concentration as seen in Figure 16.

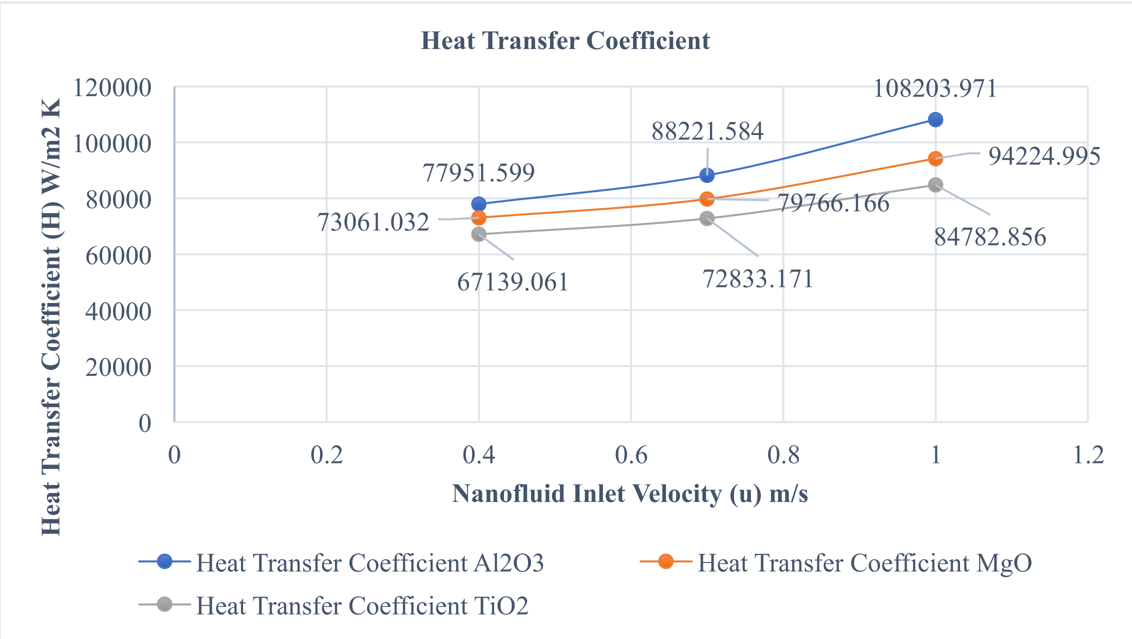

Figure.17 Heat Transfer Coefficient between Al_2O_3, TiO_2 and MgO at 1.5% concentration

Again the change in heat transfer coefficient of Al_2O_3 from 0.4m/s to 0.7m/s at 1.5% concentration is 13.17% and 22.65% from 0.7m/s to 1m/s inlet velocity. Whereas the percentage change in heat transfer coefficient of TiO_2 are 8.5% and 16.41% respectively. Similarly, the values of MgO are 9.18% and 18.13% for the two inlet velocity difference at 1.5% concentration as in Figure 17.

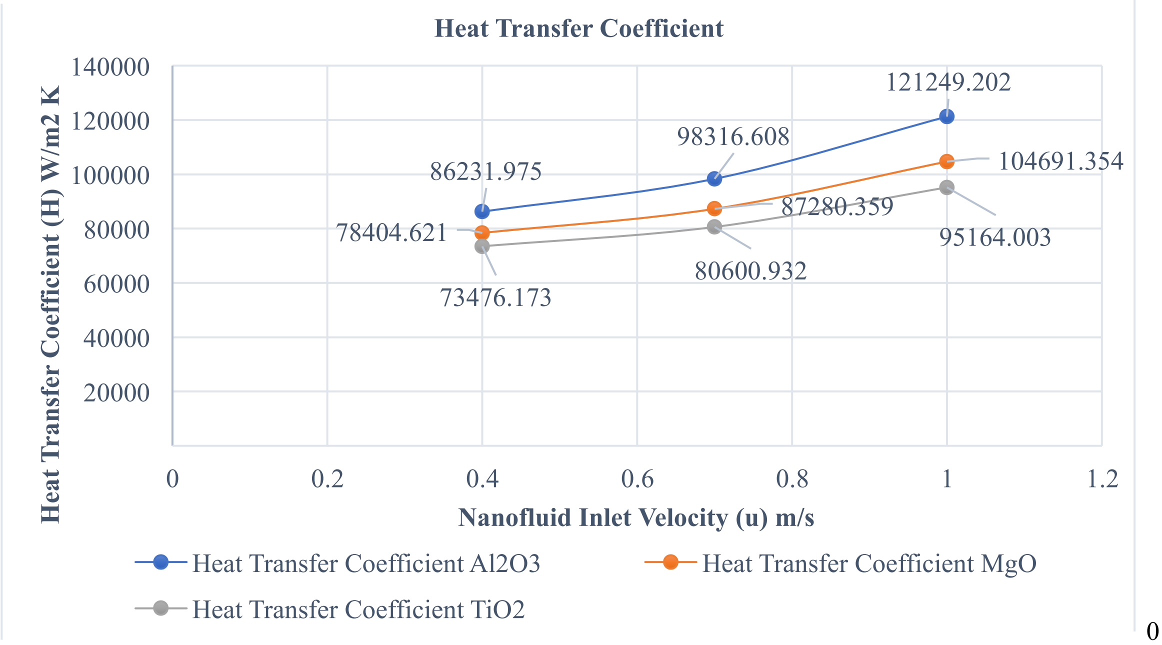

Figure.18 Heat Transfer Coefficient between Al_2O_3, TiO_2 and MgO at 2% concentration

The change in heat transfer coefficient of Al_2O_3 from 0.4m/s to 0.7m/s inlet velocity at 2% concentration is 14.02% and 23.33% from 0.7m/s to 1m/s inlet velocity. Whereas the percentage change in heat transfer coefficient of TiO_2 are 9.7% and 18.07% respectively. Similarly, the values of MgO are 11.32% and 19.95% for the two inlet velocity difference at 2% concentration as seen in Figure 18.

The results described in Figure 16, 17 and 18 shows that with increased velocity the Reynolds number increases and results in shift of flow regime from laminar to turbulent or increases turbulent intensity. Also, with increased velocity the rate of mass flow increases which allows the fluid to absorb more heat per unit time, effectively increasing overall heat transfer rate.

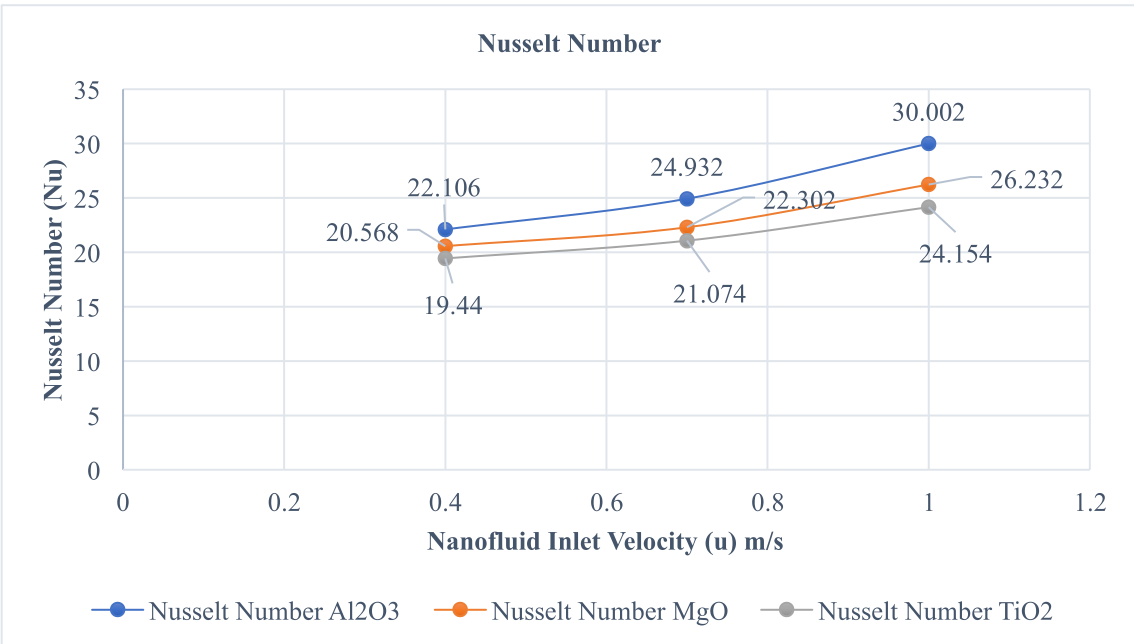

Figure.19 Nusselt Number between Al_2O_3, TiO_2 and MgO at 0.8% concentration

The percentage change in Nusselt number of Al_2O_3 from 0.4m/s to 0.7m/s at 0.8% concentration is 12.78% and 20.34% from 0.7m/s to 1m/s inlet velocity. Whereas the Nusselt number of TiO_2 varies from 8.41% and 14.62% respectively.

Similarly, the values of MgO changes from 8.43% and 17.62% for the two inlet velocity difference at 0.8% concentration as can be seen in Figure 19.

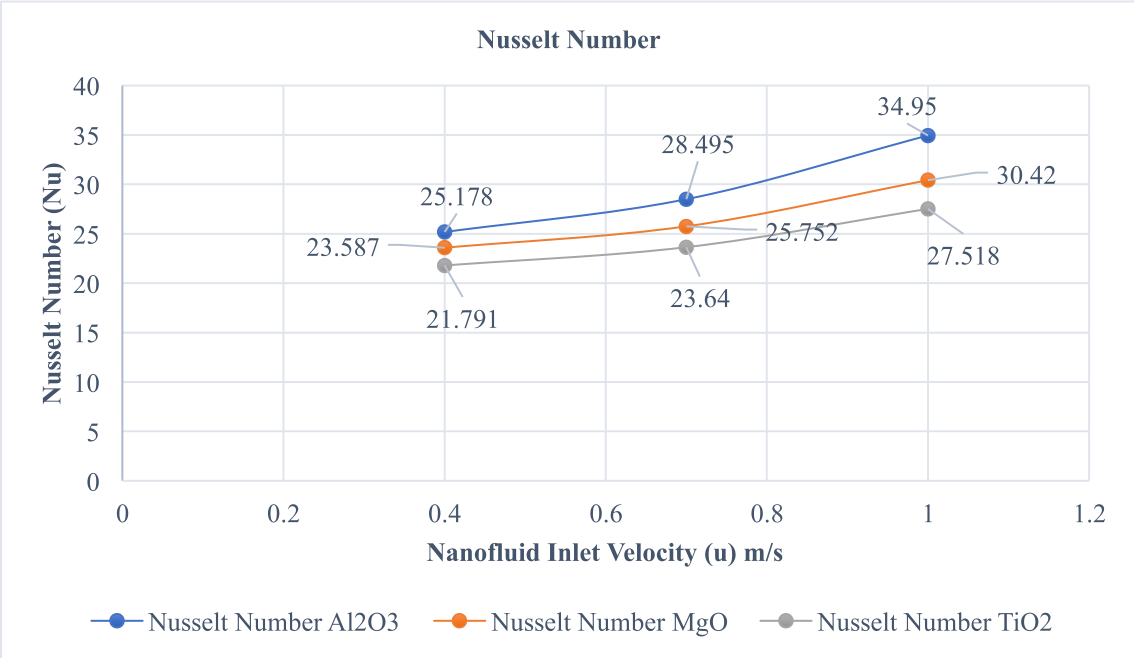

Figure.20 Nusselt Number between $Al_2O_3$3, TiO_2 and MgO at 1.5% concentration

The Nusselt number percentage change for Al_2O_3 from 0.4m/s to 0.7m/s at 1.5% concentration is 13.17% and 22.65% from 0.7m/s to 1m/s velocity. Whereas the percentage change in Nusselt number of TiO_2 is 8.48% and 16.40% respectively. Similarly, the values of MgO varies from 9.18% and 18.13% for the two inlet velocity difference at 1.5% nanofluid concentration as can be seen in Figure 20.

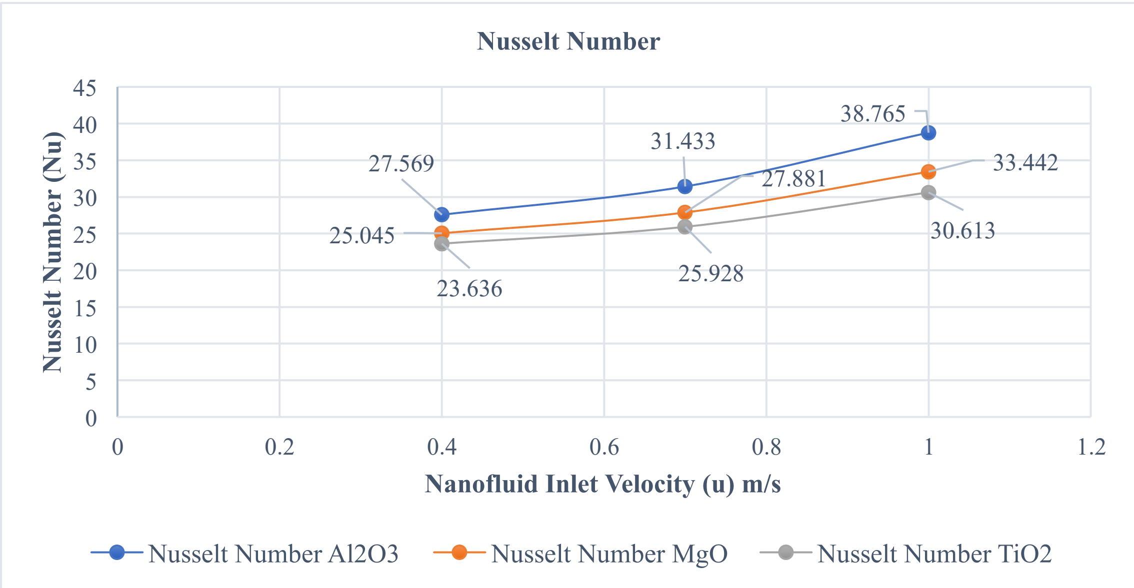

Figure.21 Nusselt Number between Al_2O_3, TiO_2 and MgO at 2% concentration

In Figure.21 the Nusselt number percentage change for Al_2O_3 from 0.4m/s to 0.7m/s at 2% concentration is 14.02% and 23.32% from 0.7m/s to 1m/s. Whereas the percentage change in Nusselt number of TiO2 is 9.7% and 18.07% respectively. Similarly, the values of MgO varies from 11.32% and 20% for the velocity differences at 2% nanofluid concentration.

The result shown in Figure 19, 20 and 21 also indicates that with increasing velocity and concentration Nusselt number of all the three nanofluids increases with Al_2O_3 exhibiting the highest value. Since Nusselt number is directly proportional to Reynold's number which indicates increased turbulent flow, thus enhancing convective heat transfer.

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With higher velocity the momentum of fluid increases, which increases the ability to transport the thermal energy from the surface of heat exchanger which enhances the temperature gradient at the wall, raising the Nusselt number.

IV. CONCLUSION

From the above data it is found that the heat transfer of Aluminium oxide is better in comparison to Titanium Oxide and Magnesium Oxide. Similarly the performance of MgO is better compared to Titanium Oxide. The heat transfer of the exchanger improves with change in velocity w.r.t to change in nanofluid concentration.
Increased velocity promotes better turbulence and mixing resulting in more efficient heat exchange whereas higher nanofluid concentration improves thermal conductivity and specific heat and other properties which may help in compact heat recovery systems.
However in practical scenario with increased concentration, there will be an increased in pressure drop, which will require more pumping power or may lead to agglomeration.
Further improvements can be done on the quality of the computational mesh. High-quality mesh will give more accurate results but would demand significantly higher computational resources and time. Optimizing these factors could enhance the reliability of the simulation outcomes.
For future work, research can be done on optimization of STHE design by experimenting with alternative baffle designs and configurations, different tube designs (e.g. hexagonal, twisted tubes, mini channels, etc.), and spacing or flow orientation. Exploring the effects of hybrid nanofluid could also offer valuable insights into improving thermal performance.

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