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Heat transfer Analysis of K-C-S_{nm} molten salt nanofluid in circular tube using CFD

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ABSTRACT

Since its discovery two decades ago, researchers in the field of nanofluid have made significant progress. Because of their remarkable thermophysical characteristics, these liquid mixes with low amounts (10% by volume) of nanometric size solid particles (100 nm) in suspension offer a considerable promise for thermal management applications. So-called classical nanofluids (based on water or industrial oils) have been widely explored in the past, with a particular emphasis on the increase in thermal conductivity found. A huge number of publications have published and evaluated experimental data, processes, and models related to these materials.In recent years, a novel class of nanofluids based on inorganic salts has been created with the goal of storing and transmitting thermal energy at high temperatures. Because of the presence of nanometric particles, these Molten Salt-Based Nanofluids (MSBNFs) have a significant rise in specific heat. Traditional nanofluids, on the other hand, have a lower specific heat than the base fluid. This unexpected behaviour has sparked a controversy in the scientific community, which is now grappling with these contentious findings as well as a lack of theories and models for these materials.A 3-dimensional numerical (3-D) simulation was used to evaluate the forced convection heat transport of molten salt nanofluid in a circular tube in this study. The heat transport physiognomies of a molten salt nanofluid in a circular tube were studied using the simulation tool ANSYS 17.0. The effect of nanofluid on heat transfer and fluid flow in a heat exchanger was tested and observed.

Keywords: Nanofluids, Molten Salts, Reynold's number, Heat transfer, Nusselt Number, CFD.

I. INTRODUCTION

In the last several decades, nanotechnology has become a worldwide revolution. The ability to manipulate materials at the atomic and molecular level has resulted in astonishing properties and qualities previously unimagined.

In the context of this extensive field of study, nanofluids have lately emerged as a viable material for heat transport and storage. They are made up of a base fluid in which nanometric sized solid particles (less than 100 nm) are scattered in volume concentrations of less than 10% [1]. The presence of nanostructures in a fluid produces an abnormal increase in its heat transfer rate, with a particular emphasis on its thermal conductivity [2, 3].Many other researchers have similarly increased thermal conductivity in a wide range of nanofluids.

As base fluid additives, carbon-based nanostructures and/or ceramic and metallic NPs have been employed. The study of water-based nanofluids has resulted in a vast number of papers.

Several industrial processes, however, necessitate the use of fluids that operate at temperatures greater than those suited for the aforementioned fluids. They are especially important in Concentrated Solar Power (CSP) facilities since their production is dependent on the effective conversion of solar thermal energy into electricity at temperatures above 300 °C. Thermal energy is now transported using industrial oils known as Heat Transfer Fluids (HTFs), which are thermally stable up to 400 °C. In recent years, the usage of molten salts as HTFs has been put into reality.

They enable operating in a broader temperature range, enhancing process efficiency. Furthermore, the use of molten salts as Thermal Energy Storage (TES) material is prevalent in CSP. The primary benefits of employing molten salts for these applications are their low cost and thermal stability at higher temperatures (600 °C). Their limited heat transmission rate, on the other hand, hinders their industrial application. The advancement of their thermophysical qualities (specific heat, c_p, and thermal conductivity, k) is critical to the advancement of TES systems and novel HTFs in CSP plants.Recent studies have shown that molten salt Nano fluid formed by adding nanoparticles in molten salt may have a significantly greater basic thermal potential and thermal conductivity than its base molten salt. Research on molten salt Nano-fluid forced convection heat transfer is therefore insufficient.

II. LITERATURE REVIEW

Molten salts have gained popularity as working fluids for high temperature processing applications and thermal-fluidics applications over the last two decades due to their stability at elevated temperatures, low vapour pressures, broad operating temperature ranges, minimal environmental footprint, ease of materials handling, low materials costs, and safety. Molten salts are used as engineering fluids in a variety of applications, including solar power production, advanced nuclear reactors, chemical refining, and energy storage. Concentrating Solar Power (CSP) plants, in particular, are gaining popularity worldwide.

The goal of this analysis is to highlight the complexity of experimental heat transfer investigations employing molten salts, given the increasing frequency of molten salts in the contemporary research literature. The goal of this analysis is to investigate the observations in the literature objectively and explore their implications. The goal of this study is to identify prospective research needs and paths based on past literature debates and implications. As a result, a summary of current advancements involving molten salt mixes or eutectics is offered (with a brief overview of patterns in their thermo-physical characteristics).This paper examines recent experimental discoveries concerning forced convection heat transfer for molten salt eutectics with the goal of establishing possible research avenues and technology needs.

Bin et al. (2009)in a stainless steel concentric tube, we performed turbulent convective heat transfer tests using $LiNO_3$. Mineral oil flowed through the annulus to cool molten LiNO3 flowing through the inner tube. The predictions using the Dittus-Boelter and Colburn equations were up to 25% and 18% higher than the experimental results, respectively. [1].

Yang et al. (2010)the heat transfer increase gained by employing a spiral tube instead of a smooth tube for receiver tubes in a Concentrated Solar Power (CSP) plant receiver was explored. The working fluid was a ternary nitrate eutectic of KNO_3–$NaNO_2$–$NaNO_3$ (Hitec salt at 53:7:40 by mass fraction). The test portion was likewise a heated 316L Stainless Steel spiral tube, according to the authors. The experimental results show that heat transfer performance in a spiral tube may be improved by up to three times over that of a smooth tube for Reynolds numbers ranging from 15,000 to 55,000. [2].

Lu et al. (2013)a series of forced convective heat transfer tests were carried out to evaluate the efficacy of spirally grooved and transversely grooved tubes to that of smooth tubes. Hitec salt was used as the working fluid. Stainless steel tubes were used to construct the test portion. In general, transverse and spiral grooves increased heat transfer by up to 1.4 and 1.5 times, respectively, as compared to smooth tubes with Reynolds numbers ranging from 5000 to 15000. [3].

Chen et al. (2016)the heat transfer performance of Hitec salt was tested in a salt-to-oil concentric tube heat exchanger with hot salt flowing through the inner tube and oil flowing through the outer tube. On the molten salt side, the Reynolds number ranged from 10,000 to 50,000, while the Prandtl number ranged from 11 to 27. In the totally turbulent domain, the experimental results show that the observed heat transfer coefficient on the molten salt side was within 7% of the values anticipated by the Gnielinski correlation and within 8% of the values predicted by the Sider-Tate correlation. [4].

Du et al. (2017)in a shell and tube heat exchanger with segmented baffles, the heat transfer performance of Hitec salt in a transitional flow regime was examined. With cooling oil running down the tubes, molten salt was poured through the shell side and around the tube bundles. With a maximum variance of 7.1 percent, the observed heat transfer coefficient on the molten salt side corresponded with classical Kern correlation. [5].

Hu et al. (2017) investigated the natural convection heat transfer of eutectic binary nitrate salt-based Al_2O_3 molten salt nanofluids in solar power systems. The result shows that the nanofluids with a 1.0% mass concentration of Al_2O_3 nanoparticles exhibit the best heat transfer performance [6].

Qian et al. (2017) studied the heat transfer performance of Hitec salt in a gas cooled shell and tube heat exchanger (finned tubes) with salt flowing internally through the tubes. The tests ranged from laminar flow to transition flow regimes (Reynolds number ranged from 987 to 12,000) and Prandtl number ranged from 9.8 to 18.9. The experimental data for Nusselt number was found to be within ± 15% of the predicted values [7].

Chen et al. (2018) improved the heat transfer performance of **Chen et al. (2016)**'s experimental setup by substituting the inner tube with a transversely grooved tube. Oil flowing through the outer tube cooled the heated salt passing through the transversely grooved inner tube. On the salt side, the Reynolds number varied from 300 to 60,000, while the Prandtl number varied from 11 to 27. When comparing the grooved tubes to the smooth tubes, the scientists found that the grooved tubes had a 60% increase in heat transfer values. However, no measurements were taken to determine the extent of the increase in pumping power caused by the grooves. [8].

He et al. (2019) Experiments were carried out to see how well Hitec salt transfers heat in a shell-and-tube heat exchanger without baffles. The input temperatures and flow velocities were varied in these trials. With an effective Reynolds number ranging from 400 to 2300, the molten salt was pumped in the shell (i.e., outside of the tube bundle). The seven tubes were pumped with hot water. Based on the hydraulic diameter of the flow channel, the observed values of Nusselt number on the molten salt side ranged from 20 to 100. (Which is computed based on the area of cross-section and the wetted perimeter). [9].

Hu Chen et al. (2020) The forced convection heat transfer studies were carried out in a circular tube using a promising molten salt nanofluid consisting of KNO_3–Ca $(NO_3)_2$ + 1 wt% 20 nm SiO2 nanoparticles that had previously been described (K-C-Snm). The K-C-Snm molten salt nanofluid demonstrated much superior forced convection heat transfer performance than its basic pure molten salt under the same operating conditions. The Nusselt number and convective heat transfer coefficient of K-C-Snm molten salt nanofluid were 16.3% and 39.9% higher, respectively, than pure molten salt. [10].

MSBNFs are mostly used in CSP facilities for TES and heat transmission, as previously stated. For this purpose, this material may be utilised in three distinct ways: 1) as a sensible storage medium 2) as a heat transfer fluid (HTF) and 3) as a latent heat storage medium (Nano-enhanced Phase Change Materials, or NePCMs). The following are some of the desirable characteristics of MSBNFs:

- Improved heat transfer qualities as compared to the base fluid: better thermal conductivity, specific heat, and latent heat.
- The stability of NPs dispersion in molten salt over lengthy periods of time.
- The nanostructured material is stable and does not degrade when subjected to heat cycling.
- The presence of NPs causes a little or insignificant increase in viscosity, allowing for effective pumping of the nanofluid.
- Chemical compatibility and lack of physical erosion with container materials

Although the aforementioned researchers have researched different aspects of molten salts, there has been no study on forced convection heat transfer of molten salt nanofluid. However, such research is needed for the successful application of molten salt nanofluid in industrial practice. The forced convection heat transfer of molten salt nanofluid was numerically explored in this work.

III. GEOMETRY SETUP AND MODELLING

A 3-dimensional numerical (3-D) simulation was used to evaluate the forced convection heat transfer of molten salt nanofluid in a circular tube in this study. The heat transmission physiognomies of a molten salt nanofluid in a circular tube were studied using the simulation tool ANSYS 17.0.

Hu Chen et al. (2020), a research scholar, provided the geometry for completing simulation analysis. The design of the experimental system is shown in Fig. 1; the bulk of the system is made up of a molten salt nanofluid circulation loop and a heat conduction oil circulation loop. In this experiment, heat is transmitted from molten salt nanofluid to heat conduction oil using a circular tube type heat exchanger. Figure 1 depicts the heat exchanger architecture. L is the length of the heat exchanger tube.

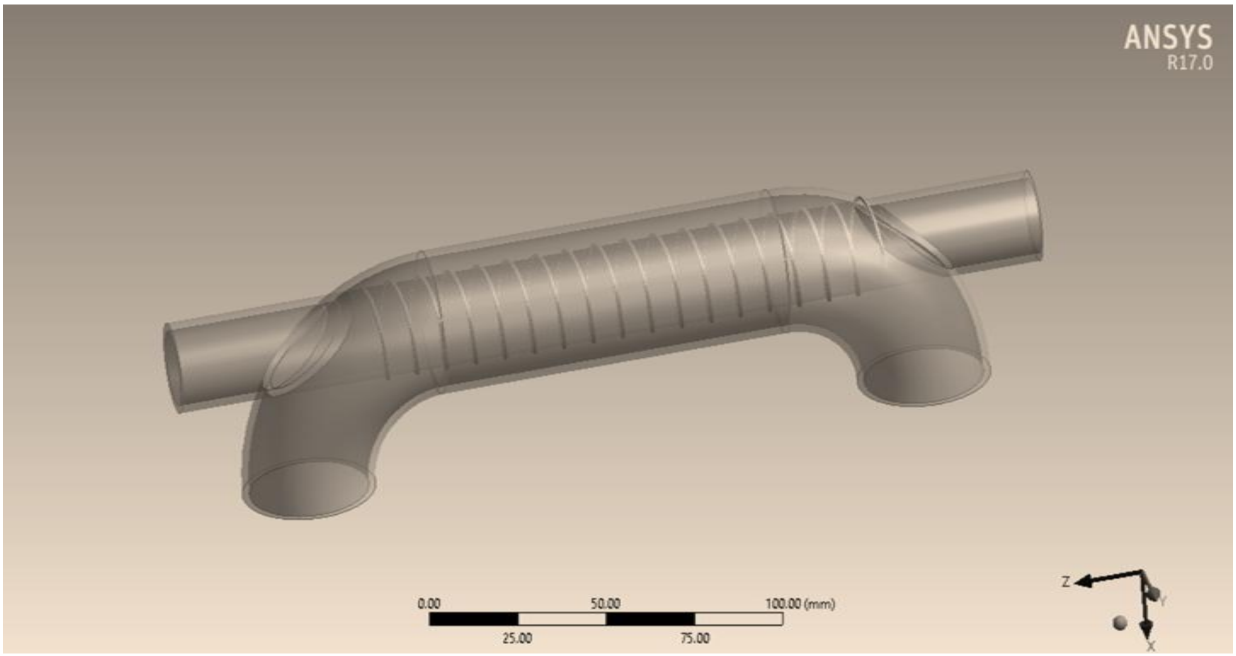

Figure 1. Computational model of heat exchanger.

In the pre-processor phase of ANSYS FLUENT R 17.0, a three-dimensional discretized model was created. Although the grid types are linked to simulation results, the structure as a whole must be discrete in the final volume; the ANSYS software generates a coarse mesh. Mesh is made up of unit-size mixed cells with triangular frontier faces (ICEM Tetrahedral cells). In this investigation, a mesh metric with a medium fluid curvature is utilised.

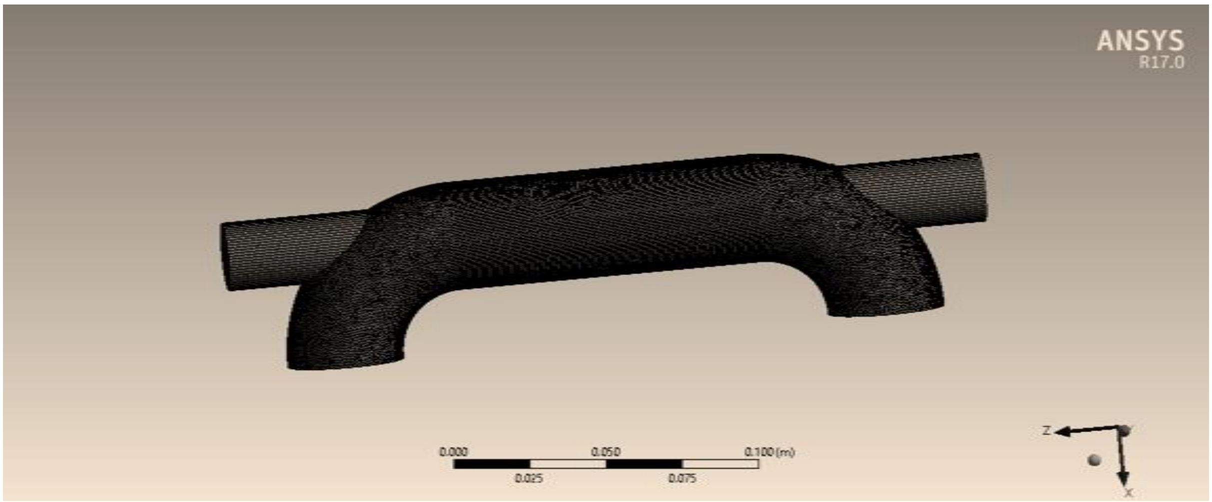

Figure 2. Meshing of heat exchanger.

Table 1. Meshing detail of model

S. No.	Parameters	
1	*Curvature*	*On*
2	*Smooth*	*Medium*
3	*Number of nodes*	*468775*
4	*Number of elements*	*1538922*
5	*Mesh metric*	*None*
6	*Meshing type*	*Tetrahedral*

The Fluent 17.0 was used to calculate computationally. In research, the approach used to differentiate the governing equations was a finite element. For this convective term, the researchers used a simpler algorithm, and for connecting calculations of the pressure and velocity the second order upwind method was implemented.

A standard k-epsilon equation was used with flow and energy equations to solve turbulence.

Which implies the following hypotheses:

1) There is negligence of thermal radiation and normal convection;
2) The average of fluid and solid properties is calculated
3) Flow is incompressible;
4) Heat transfer steady state;
5) Transitional fluid flow and turbulent regimes, and
6) The fluid is distributed uniformly between the channels and the inlet channels have a uniform velocity profile.

The numerical simulation was with a 3-Dimensional steady state turbulent flow system. In order to solve the problem, governing equations for the flow and conjugate transfer of heat were customized according to the conditions of the simulation setup.

Table 2. Thermodynamic Properties of Binary Salt and Nano-particles.

Input Parameters	*Symbols*	*Units*	*Binary Salt*	*SiO_2*	*TiO_2*
Specific heat capacity	c_p	*J/kg-K*	*1.497*	*680*	*686.2*
Density	ρ	*(kg/m^3)*	*1.835*	*2220*	*4250*
Thermal conductivity	*k*	*W/m-K*	*0.55*	*1.3*	*8.593*

Table 3. Thermodynamic Properties of KNO_3–$Ca(NO_3)_2$ + 1 wt% of 20 nm SiO_2 and KNO_3–$Ca(NO_3)_2$ + 1 wt % of 20 nm TiO_2 nanoparticles

Input Parameters	*Symbols*	*Units*	*KNO3–Ca(NO3)2 + 1 wt % of 20 nm SiO2*	*KNO3–Ca(NO3)2 + 1 wt % of 20 nm TiO2*
Specific heat capacity	c_p	*J/kg-K*	*628.694*	*658.1323*
Density	ρ	*(kg/m^3)*	*24.016*	*44.31665*
Thermal conductivity	*k*	*W/m-K*	*0.555*	*0.5638*

The discrete flow domain has been defined under sufficient limits. Inlets were allocated the mass flow rate requirements, while pressure outlet limits were allocated for outlets. The surfaces of the heat exchanger is regarded as normal wall limits. The interior walls were fitted with couplings of thermal walls.

Table 4. Details of boundary conditions.

Detail	*Value*
Molten salt nanofluid flow rate	*At different Reynold's no. 15000, 25000, and 35000*
Heat conduction oil flow rate	*0.465 kg/s*
Molten salt nanofluid inlet temperature	*300 °C*
Heat conduction oil inlet temperature	*125 °C*
Outer surfaces	*Heat flux=0*

IV. RESULTS AND DISCUSSIONS

This section is aimed at evaluating the heat exchanger thermal performance using nanofluids. The variations in the Heat transfer rate and Thermal conductanceare measured at different Reynold's number in order to research the performance of the heat exchanger using nanofluids subject to flow.

4.1. Data reduction equations

The values of Nusselt number, and Heat transfer coefficient calculated from the CFD modeling On the basis of temperature of hot and cold fluid obtained were compared with the values obtained from the analysis performed by **Hu Chen et al. (2020)**.

The data reduction of the measured results is summarized in the following procedures:

The Reynolds number is given by,

$$Re = \frac{\rho V D}{\mu}$$

The mass flow rate is calculate on the basis of below formula,

$$\dot{m} = \dot{\rho} A V$$

Where, ρ is the density of fluid, A is the cross sectional area of the pipe and V is the velocity of fluid.

Therefore, for fluid flows in a concentric tube heat exchanger, the heat transfer rate of the hot fluid in the outer tube can be expressed as:

$$q_h = \dot{m}_h c_{ph}(T_{hi} - T_{ho})$$

Where $\dot{m}_h$ is the mass flow rate of hot fluid, c_{ph} is the specific heat of hot fluid, T_{hi} and T_{ho} are the inlet and outlet temperatures of hot fluid, respectively.

While, the heat transfer rate of the cold fluid in the inner tube can be expressed as:

$$q_c = \dot{m}_c c_{pc}(T_{co} - T_{ci})$$

Average heat transfer rate is given by:

$$Q_{avg} = \frac{q_h + q_c}{2} = UA\theta_m$$

Where, $\theta_m = \frac{\theta_1 - \theta_2}{2}$

θ_m is the logarithmic mean temperature difference.

U is the overall heat transfer coefficient.

4.2. Validation of numerical computations

To validate the accuracy of developed numerical approach, comparison was made with the work reported in **Hu Chen et al. (2020)**. The heat exchanger geometry that used for validation of numerical computations was considered as same as the geometry shown in Fig.1.

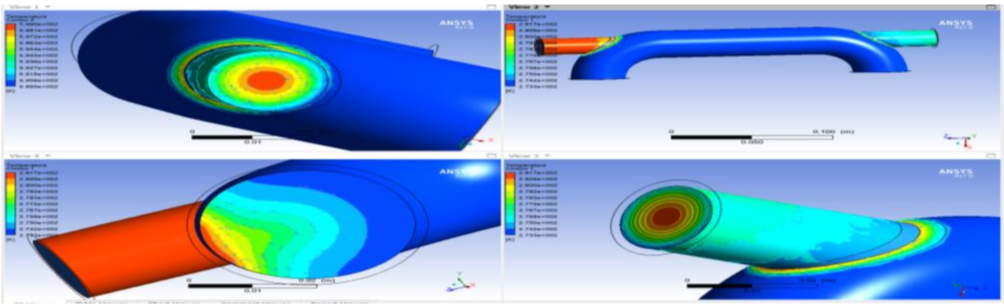

Figure 3. Temperature contour at Re = 15000 for heat exchanger using KNO_3–Ca $(NO3)_2$ + SiO2 molten salt nanofluid in a circular tube.

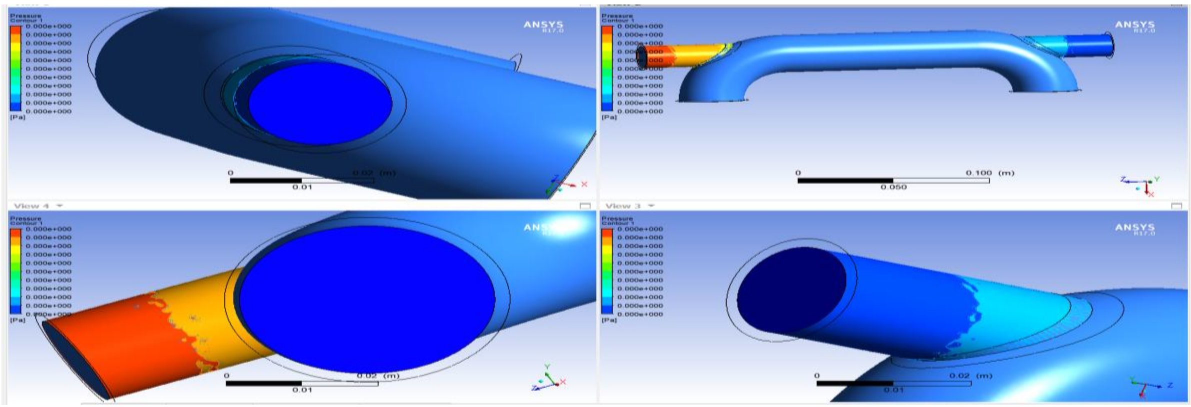

Figure 4. Pressure contour at Re = 15000 for heat exchanger using KNO_3–Ca $(NO3)_2$ + SiO2 molten salt nanofluid in a circular tube.

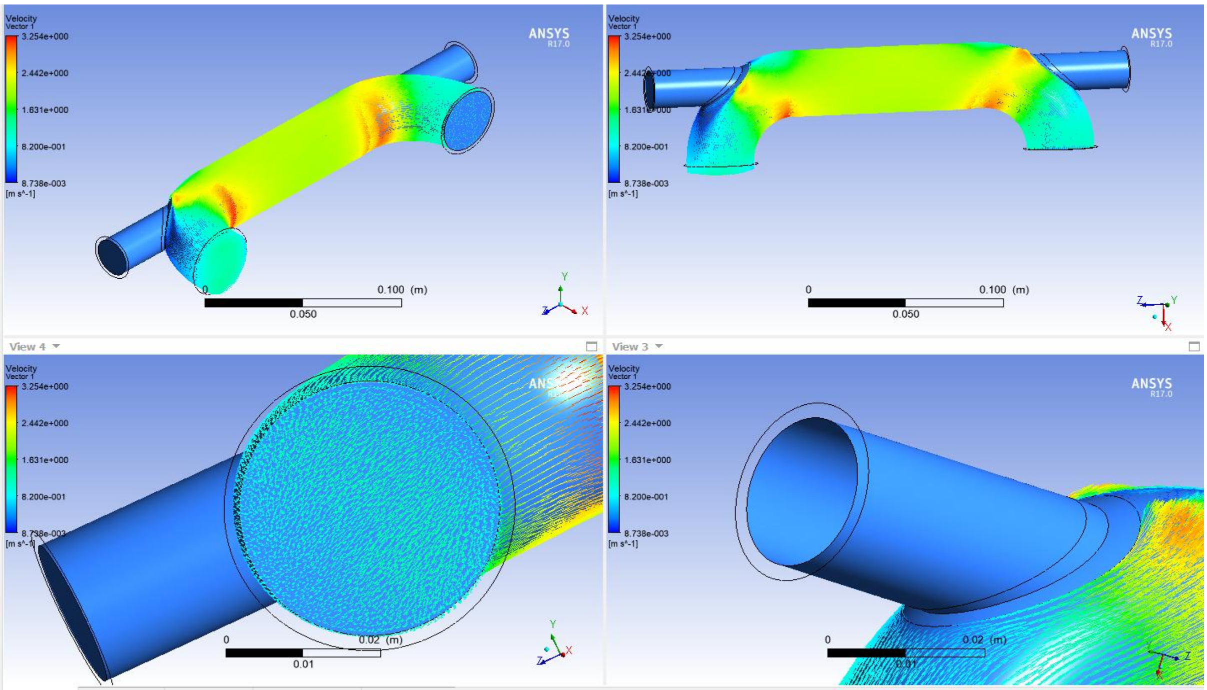

Figure 5. Velocity contour at Re = 15000 for heat exchanger using KNO_3–Ca $(NO3)_2$ + SiO2 molten salt nanofluid in a circular tube.

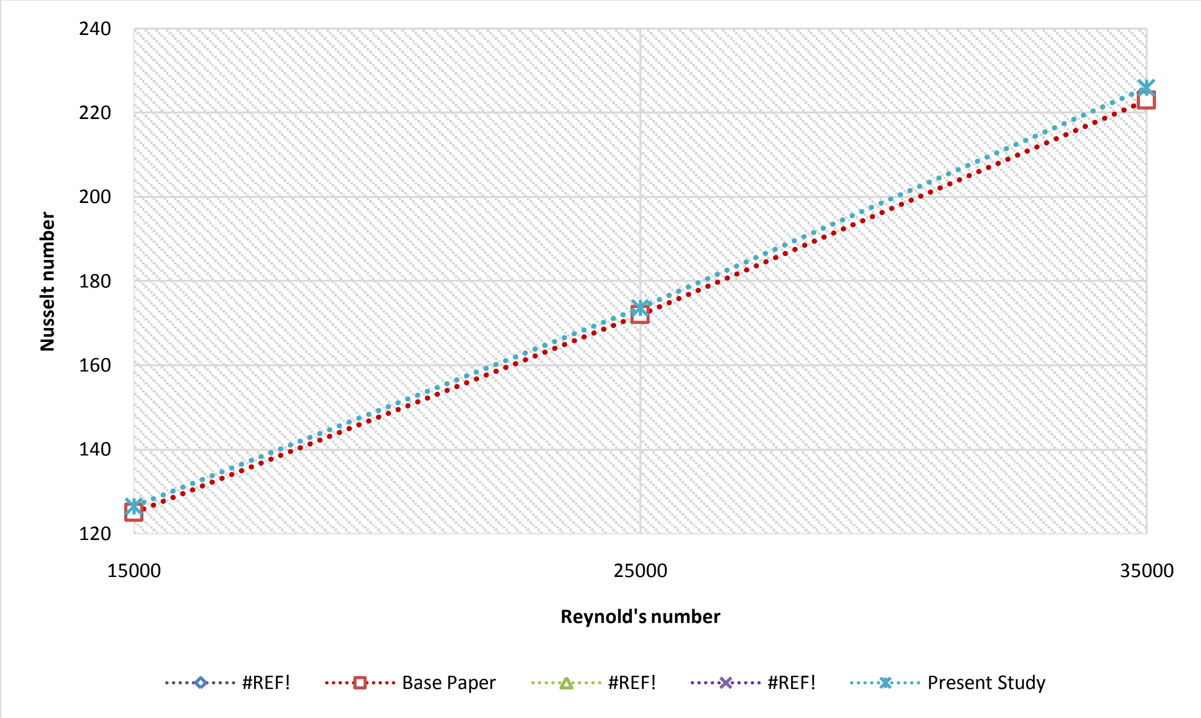

Figure 6. Values of Nusselt number calculated from the CFD modeling compared with the values obtained from the analysis performed by Hu Chen et al. (2020)for heat exchanger.

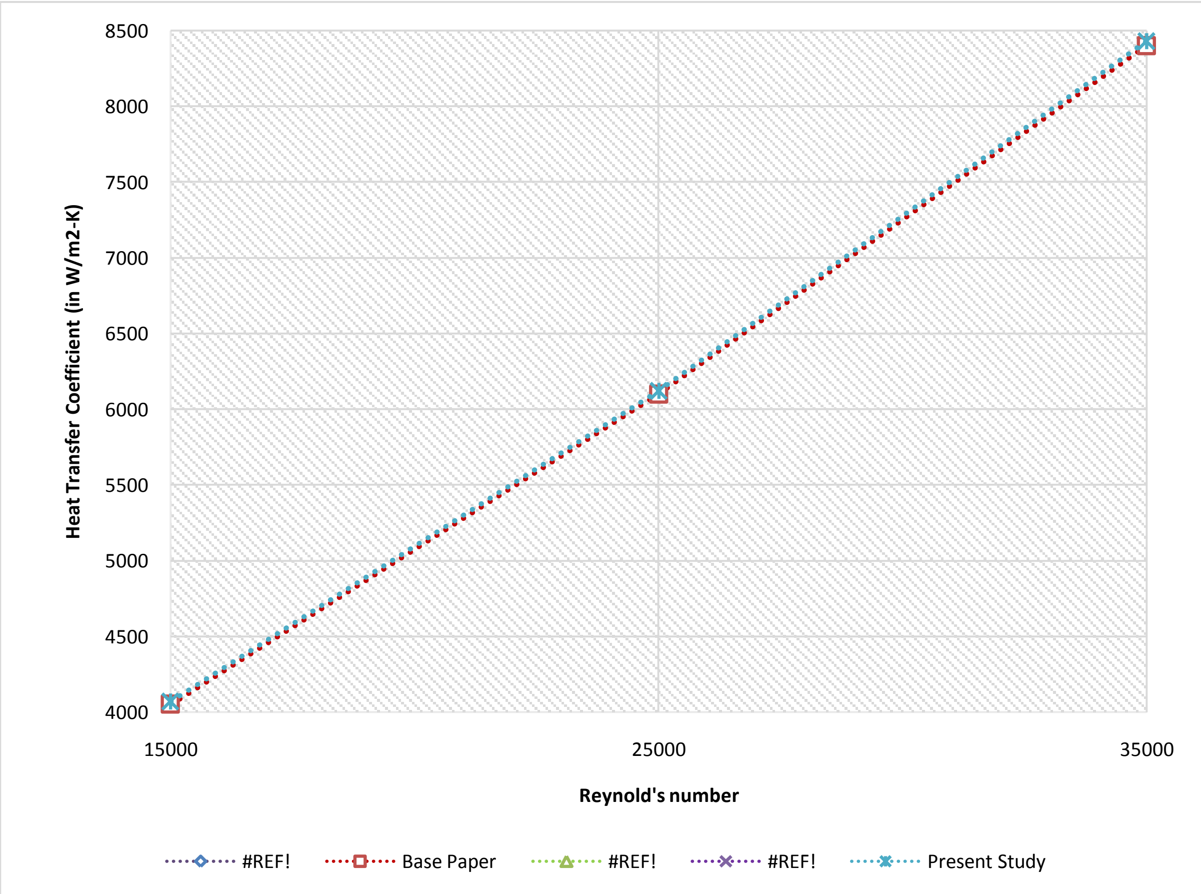

Figure 7 Values of Heat transfer coefficient calculated from the CFD modeling compared with the values obtained from the analysis performed by Hu Chen et al. (2020)for heat exchanger.

From the above graph, it is found that the value of Nu number and heat transfer coefficient calculated from numerical analysis is closer to value of Nu number and heat transfer coefficient obtained from the base paper, which means that numerical model of heat exchanger using nanofluid, is correct.

There is much lesser difference between experimental and numerical values.

4.3. Effect of suspension of TiO_2 Nano-particles in the molten salt

The numerical and experimental data show that the variations in the values of the Nusselt number and heat transfer coefficient are qualitatively consistent. As a result, we use a volume concentration of 1 percent to investigate the effect of TiO2 Nano-particle suspension in molten salt on thermal augmentation. The boundary conditions were the same as those considered during the heat exchanger study. In next, the thermal characteristics of Nano fluids are discussed in order to calculate the influence of various Nano particles on the Nusselt number and heat transfer coefficient.

For Re = 15000

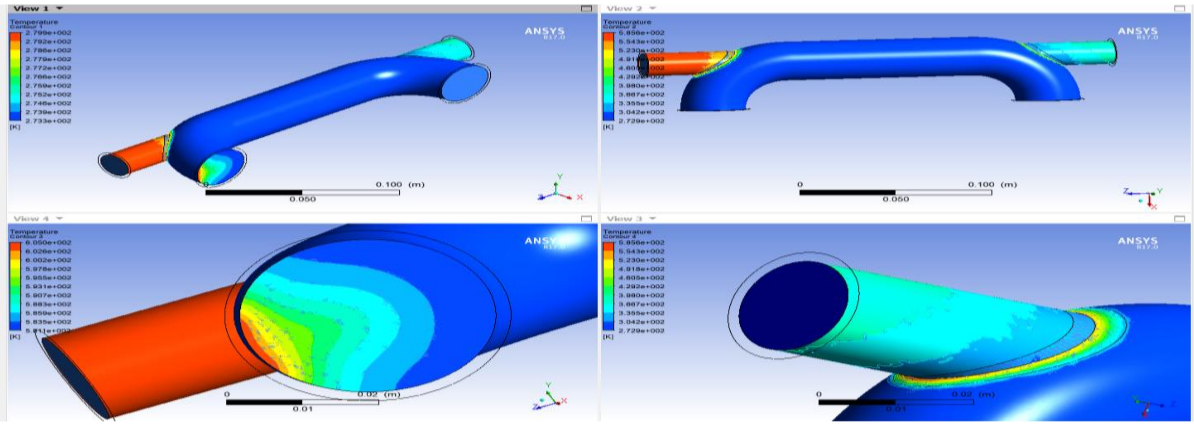

Figure 8. Temperature contour at Re = 15000 for heat exchanger using KNO_3–Ca $(NO3)_2$ + TiO2 molten salt nanofluid in a circular tube.

For Re = 25000

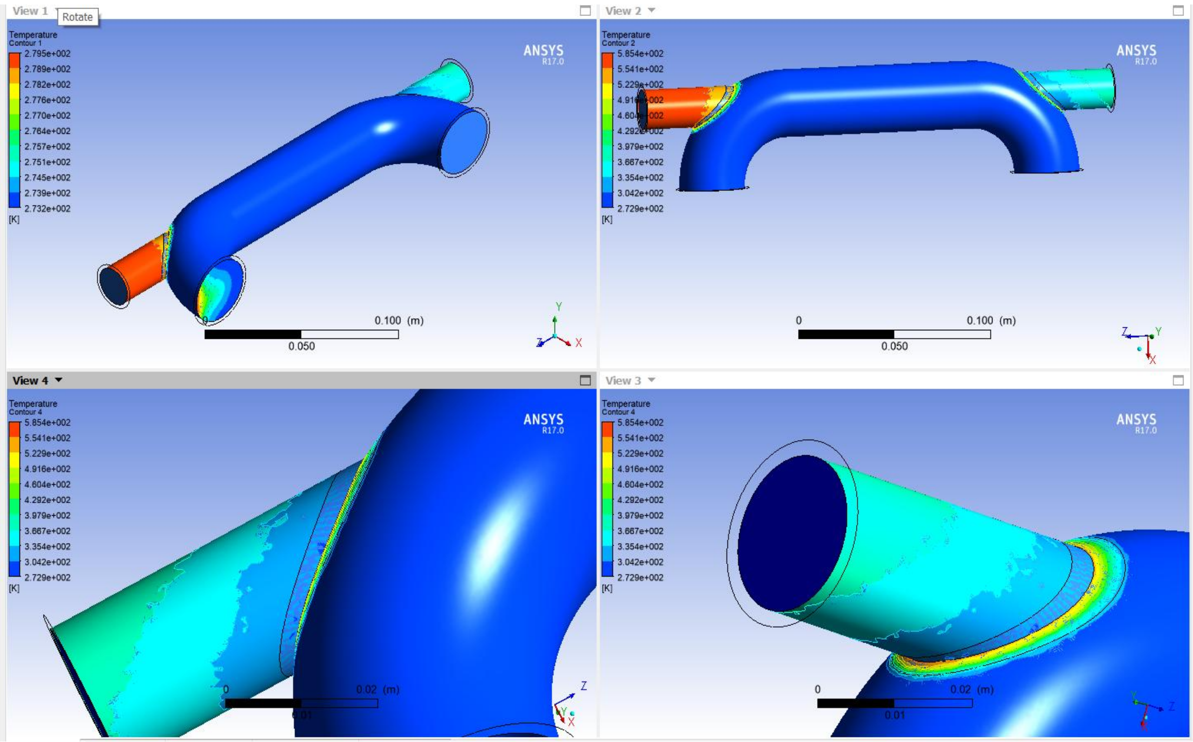

Figure 9. Temperature contour at Re = 25000 for heat exchanger using KNO_3–Ca $(NO3)_2$ + TiO2 molten salt nanofluid in a circular tube.

For Re = 35000

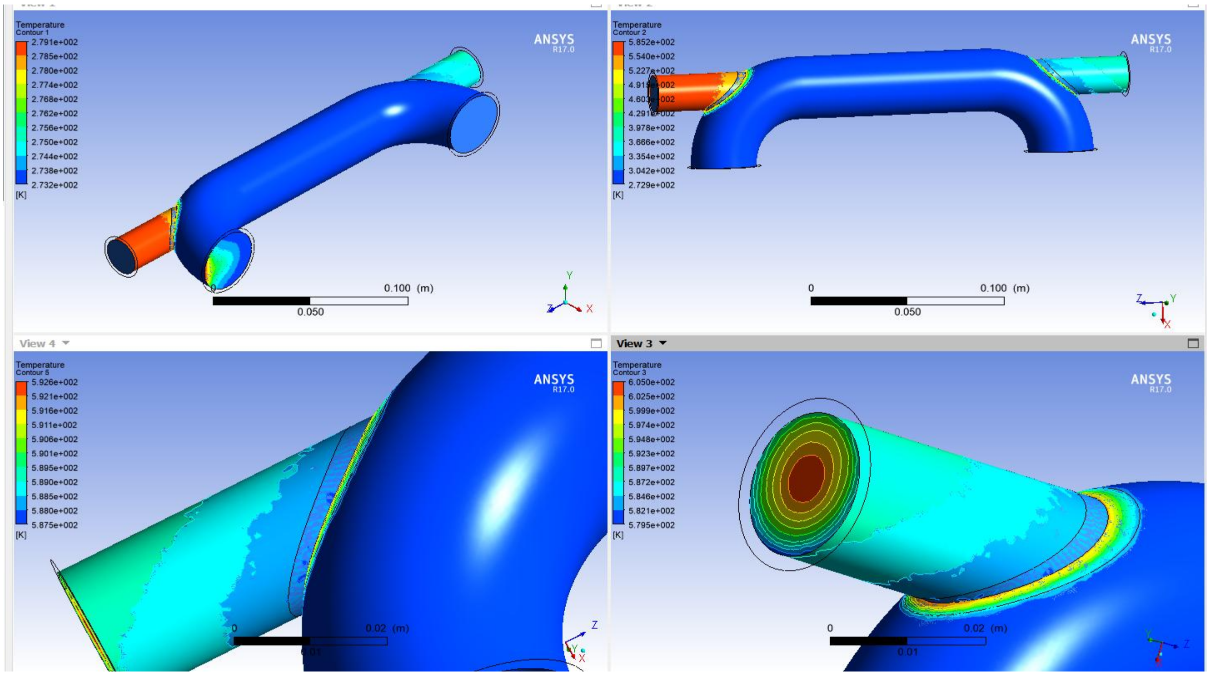

Figure 10. Temperature contour at Re = 35000 for heat exchanger using KNO$_3$–Ca (NO3)$_2$ + TiO2 molten salt nanofluid in a circular tube.

4.4. Comparison between Nanofluid fluid i.e. SiO$_2$/Molten Salt and TiO$_2$/Molten salt at different Reynold's number

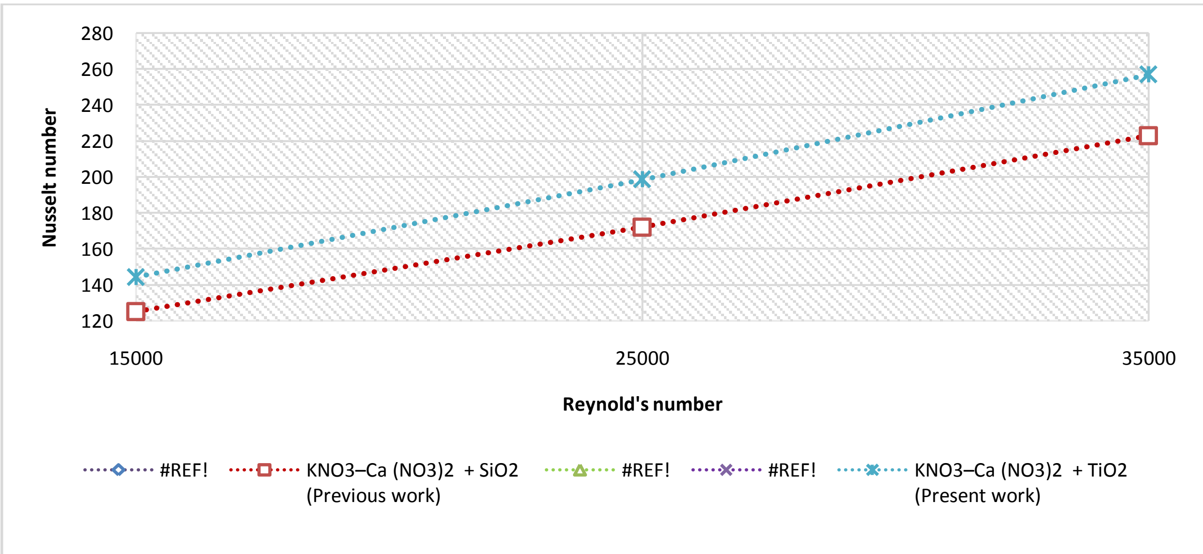

Figure 11. Nusselt number values comparison for Nanofluid fluid i.e. SiO$_2$/Molten Salt and TiO$_2$/Molten salt at different Reynold's number.

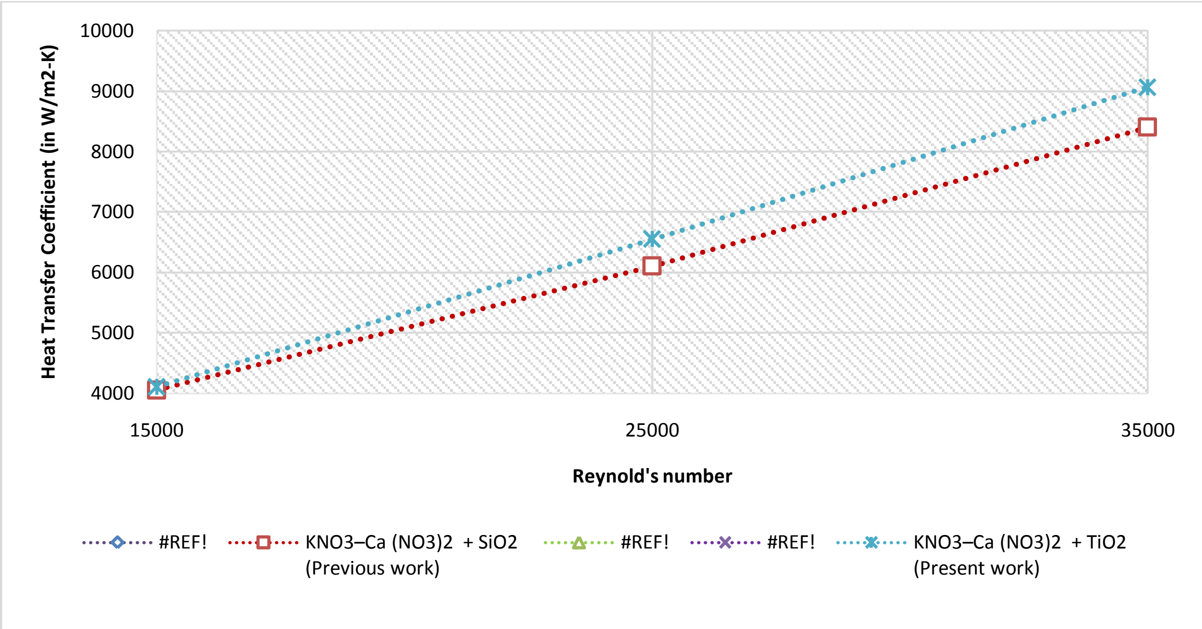

Figure 12. Heat transfer coefficient values comparison for Nanofluid fluid i.e. SiO_2/Molten Salt and TiO_2/Molten salt at different Reynold's number.

V. CONCLUSIONS

The effect of nanofluid on heat transfer and fluid flow in a heat exchanger was tested and observed. Based on the results presented, the following conclusions may be drawn:

- Under the same operating circumstances, the molten salt TiO_2 nanofluid performed somewhat better in forced convection heat transfer than the molten salt SiO_2 nanofluid.
- Molten salt TiO_2 nanofluid showed a 14.79 percent greater Nusselt number than molten salt SiO_2 nanofluid.
- The heat transfer coefficient of molten salt TiO_2 nanofluid was 7.88% higher than that of molten salt SiO_2 nanofluid.

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