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Thermal Performance of Diffusion-Bonded Compact Heat Exchangers using Al_2O_3/Water Nanofluid

Vishal Deshmukh[1], Prof. Animesh Singhai[2]

[1]Research Scholar, [2]Professor,

[1,2]Trinity Institute of Technology and Research, RGPV Bhopal, Madhya Pradesh, India

ABSTRACT

The value of compact heat exchangers (CHEs) has been recognised in aerospace, automotive, gas turbine power station, and other industries for the last 50 years or more. This is attributed to many reasons, for example manufacturing restrictions, often high efficiency requirements, low cost, and the use of air or gas as one of the fluids in the exchanger. Together with new and improved forms of CHEs, these advances are an excellent opportunity to bring compact heat exchangers into the process industry, particularly where saving energy is an essential target. High energy prices are also encouraging companies to use energy saving strategies at their plants as much as possible. During decades, attempts to increase heat transfer, decrease heat transfer times and eventually improve energy efficiency have been made. Recent advancements in nanotechnology have facilitated the creation of a new type of liquids called nanofluids. Most theoretical and computational experiments have shown that nanofluids demonstrate an improved coefficient of heat transfer relative to their base fluid. This CFD research explores the impact on the performance of straight-square compact heat exchangers from Al2O3 / water nanofluid flow. The Al2O3 / water nanofluids with three weight fractions of nanoparticles (i.e. 0.4, 0.8, and 1.2 percent) were used. The effect of nanofluid were measured and observed to influence the heat transfer and flow of fluids in a straight-square compact heat exchanger. The following conclusions can be drawn based on the provided results, the thermal conductance are approximately 29% higher and the heat transfer are approximately 35 % higher in comparison with the conventional fluid i.e. water.

KEYWORDS: *Compact heat exchanger, Nano-fluids, CFD, Heat Transfer and Thermal conductance*

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I. INTRODUCTION

Shell and tube or variants constitute approximately 35% of the total of heat exchangers used in the petroleum and process industries, becoming by far the most common technology [1, 2]. Although these types of heat exchangers are efficient and durable, they are not ideal for use in certain applications because of their wide volumes and footprint areas [1, 3]. Their main characteristic is the large surface area for a fixed volume, which makes compact heat exchangers very effective. These devices are modern and effective, but still worth a lot of research worldwide, even though they are recently significantly advanced.

Compact heat exchangers were designed for applications where small weight and space requirements are mandatory, as seen in the fields of aerospace, maritime, and automotive. Hot and/or cold streams will flow through non-circular cross-section ducts, i.e. triangular or rectangular, among other geometries in many heat exchangers particularly the compact ones. Normally, the lengths of these ducts are short. The system can function in several regimes, ranging from laminar to turbulent. A **compact heat exchanger (CHE)** is a piece of equipment designed to effectively convert heat from one medium to another, characterized by a wide area-to - volume ratio of heat transfer (minimum 300 m^2 / m^3), high coefficients of heat transfer (up to 5000 W / m^2 K), limited flow passages.

1.1. Diffusion bonded compact heat exchangers

In general, the compact heat exchanger is produced from a large number of channel panels, chemically etched or water – jet machined [4, 5].

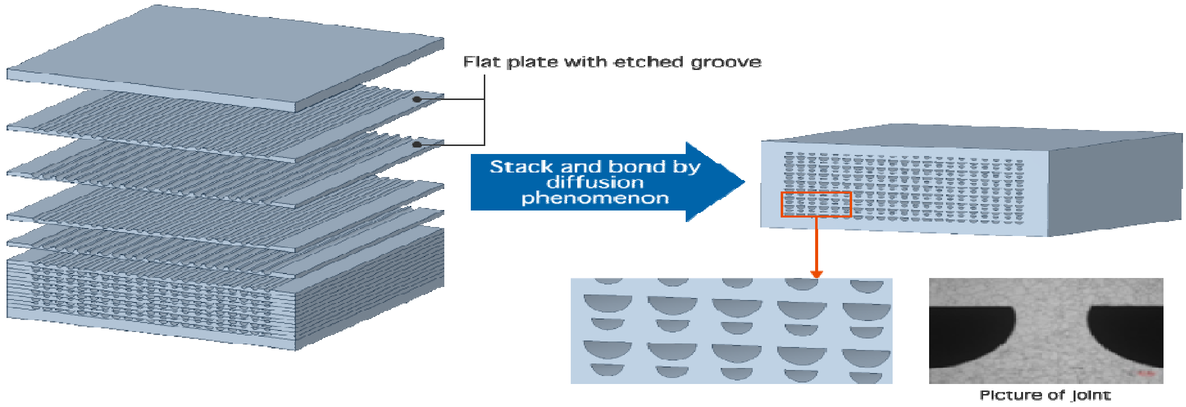

Figure 1 Diffusion bonded micro channel heat exchanger.

A diffusion bonding technique is applied following a stacking procedure to create the core. This technology provides excellent mechanical strength at the interface, allowing these exchangers to withstand extremely high pressures which can reach 50 MPa in certain circumstances [3, 6].In addition to more common oil exploration systems, advanced high-temperature reactors, solar concentrated applications, air respiration synergetic and rocket engines, compact heat exchangers and diffusion bonding have been used over the years [7–10], among others.
In order to reduce the size and costs of the heat exchanger, improving the heat transfer by different techniques has received great attention over the years. Different heat exchanger technologies have, as effective techniques, been developed to increase heat transfer rate:
1. Nanofluids
2. Insert heat exchanger turbulators
3. Roughening surfaces. While the mixture of all three methods or two can be used for a better heat transfer.

1.2. Nanofluids
Researchers have sought in recent years to minimise heat exchangers' size and weight. Some companies uses conventional fluids such as gasoline, water and ethylene glycol. Heat transfer fluid is weaker than solids in terms of thermal conductivity because of its poor thermal conductivity; therefore, it limits the quality and compactness of engineering goods.

Some techniques are used to increase the heat transfer performance. They are each incorporated into general heat transfer fluids by small solid particles such as metallic, non-metallic and polymeric. In many applications, if millimetres or even micro particles are used, they cannot be used, although the thermal efficiency improves. When problems are caused, such as quick partitioning, flow channel blocking, lower stability and increased liquid pressure drops. These problems can be overcome with the use of nanometer-sized particles dispersion. Nanoparticles with a size of 1–100 nm are used for this same reason in base fluids instead of these particles. These suspensions, known as **nanofluids**, are used in many industries and are one of the novel developments. Most theoretical and computational experiments have shown that nanofluids demonstrate an improved coefficient of heat transfer relative to their base fluid and increase dramatically with increased concentration of nanoparticles as well as number of Reynolds.

II. LITERATURE REVIEW
As the need for more effective heat transfer systems grows, researchers have been using various heat transfer improvement techniques since the mid-1950s. The substantial growth in the number of research publications devoted to this topic has demonstrated, to date, a substantial improvement in the importance of heat transfer technology.

A significant amount of theoretical as well as empirical and quantitative study has been carried out to improve the transfer of heat. A brief review of the related literature is described in this chapter to show the degree of work already published in the open literature on the development of the heat transfer by the application of nano fluids, and use of compact heat exchanger.

2.1. Previous work
Owing to the heat transfer properties of nanoparticles, industries such as solar synthesis, gas sensing, biological sensing, pharmaceutical, nuclear reactors, the petroleum industry, etc. have followed the idea of using nanoparticles in their respective fields to boost the heat transfer performance of regular fluids.Thermal conductivity is increased by the inclusion of nanoparticles as technically demonstrated by **Choi et al. (2001)** [11].

Masuda et al. (1993) and **Minsta et al. (2009)** have shown that the incorporation of a limited volume of nano-particles < 5 per cent › has resulted in a major increase (10-50 per cent) in the thermal conductivity of simple fluids [12,13].

Kim et al. (2007) examined the critical role of nanofluids in the field of nuclear physics. Proven nanofluids will increase the efficiency of any water-cooled nuclear device system. Possible uses include pressurized water reactor, main coolant, standby protection devices, acceleration targets, plasma diverters, and so on [14, 15].

From Jackson's (2007) point of view, the critical heat flux may be increased by producing a controlled surface from nanofluid deposition. The use of nanofluid will increase the in-vessel retention capability of nuclear reactors by as much as 40% [16].

Chandrasekhar et al. (2017) experimentally investigated and theoretically validated the behavior of Al_2O_3/water nanofluid that was prepared by chemical precipitation method. For their investigation, Al_2O_3/water at different volume concentrations was studied. They concluded that the increase in viscosity of the nanofluid is higher than that of the effective thermal conductivity. Although both viscosity and thermal conductivity increases as the volume concentration is increased, increase in viscosity predominate the increase in thermal conductivity. Also various other theoretical models were also proposed in their paper [17].

Hady et al. (2017) experimentally investigated the performance on the effect of alumina water (Al_2O_3/H_2O) nanofluid in a chilled water air conditioning unit. They made use of various concentrations ranging from 0.1-1 wt % and the nanofluid was supplied at different flow rates. Their results showed that less time was required to achieve desired chilled fluid temperature as compared to pure water. Also reported was a lesser consumption of power which showed an increase in the cooling capacity of the unit. Moreover the COP of the unit was enhanced by 5 % at a volume concentration of 0.1 %, and an increase of 17 % at a volume concentration of 1 % respectively [18].

Rohit S. Khedkar et al. (2017): Experimental experiments on double tube heat exchanger for water for heat transfer from nanofluids to base fluids, using nanofluids as a working fluid, with different nanoparticles. For a fixed heat transfer surface with various volume fractions of Al_2O_3 nanoparticles in simple fluids, the total heat transfer coefficient was experimentally calculated and results contrasted with pure water. The findings they found 3% of nanofluids with average heat transfer coefficients 16% higher than water show optimal efficiency [19].

Compact heat exchangers with different topologies of channels, namely: straight, zigzag, s-type, and airfoil configuration were studied in recent years.

Mylavarapu et al. (2014) the thermal-hydraulic output with helium was assessed as working fluid by the two straight, semicircular printed circuit heat exchangers (PCHE). A comparison between the model and the experimentation findings indicate that the experimental Fanning friction factor was underestimated by the theoretical models. When the transition to turbulence begins, the Nusselt number derived from their model correlate well to the experimental Nusselt number for Reynolds up to 1700. A strong agreement for the Nusselt numbers model is found for Reynolds larger than 3000 [20].

Seo et al. (2015) the thermal transport of the straight semicircular microchannel PCHE, measured by Reynolds up to 850, was examined and water was used for cold as well as hot surfaces as working fluid [21].

In a straight semicircular mini-channel PCHE with counterflow arrangement **Kwon et al. (2018)** experimentally tested the heat transfer coefficient. The PCHE was measured at cryogenic temperatures under different heat transfer conditions: single phase, boiling and condensation. The test number of Reynolds ranged from 8500 to 17 000 during the single-phase trial [22]. They contrasted their results with associations between **Gnielinski** [23] and **Peng and Peterson** [24].

Chu et al. (2018) the thermohydraulic performance of PCHE as heating exchange fluids was evaluated with a direct semi-circular channel with SCO_2 and water. The first was the water and water mixture to discover water associations for the PCHE waterside. There were two tests performed. The test shows that the association between **Gnielinski [23]** and the average of Reynolds ranges between 2800 and 6700 by 13.2 and 8.6% respectively. A mixture of SCO2 and water was used as fluids in the second test. The effects on the thermal efficiency of the PCHE were evaluated in this test for thermal properties, strain and the pseudo-critical effects. Correlations have been indicated on the SCO2 line, which are true on Reynolds, between 30.000 and 70.000, in order to quantify Nusselt numbers in conjunction with fluid properties [25].

A.P.C. Sarmiento et al. (2020) Presents an experimental and theoretical examination of the thermal efficiency of a compact heat exchanger of square direct diffusion stainless steel. The thermal characteristics of the heat exchange is predicted by a single-dimensional steady state thermal model. An experimental test apparatus was designed to verify the model and study the thermal actions of the heat exchanger. In multiple Reynolds variations, 2600 to 7500 were tested for the heat exchanger reflecting the transition to turbulent regimes. The temperatures ranged from 70 ˚C and 80 ˚C for water and between 25 ˚C and 42 ˚C at heat exchanger intake. A strong consensus was established between the experimental results and the research model [26].

The literature review strongly points to the theoretical and experimental evaluation of laminar and turbulent Reynolds numbers worked under high temperatures and pressures (supercritical fluid) in much of the work on compact heating exchangers coupled with diffusion bonding. Note that the effect of the working fluid on the compact heat exchanger is ignored in most of these works. In laminar or turbulent flow conditions the researchers constantly observed high rates of heat transfer with various kinds of nanofluids flowing in a channel. The improvement in nanofluid heat transfer depends on the particle concentration, thermal conductivity of nanoparticles and mass flow rates. Various aspects of nanofluids and various methods for the use of nano fluids to increase heat transfer rates were explored by the above researchers in many heat exchangers. The study concentrates on growing the effectiveness of nanofluid in several research papers. Some papers, however, concentrate on nanofluid and its effect, effectiveness, heat transfer and overall coefficient of heat transfer. Research clearly show that nanofluids have higher heat transfer enhancements than normal base fluids such as water, oil etc. No studies have been published on the use of nanofluids as a working medium in compact heat exchangers to the best of the authors' literature surveys.

2.2. Research Objectives

In this analysis, the thermal characteristics of a nanofluid in a straight-square compact heat exchanger was investigated using a 3-dimensional numerical (3-D) simulation where single-phase streams flow in a diffusion-bonded compact heat exchanger in the transition to turbulent regimes. The simulation programme ANSYS 17.0 was used for study of the heat transfer physiognomies of a compact heat exchanger with nano-fluids.

The main objectives of the present work are as follows:

- To analyze the thermal characteristics of straight-square compact heat exchanger using nanofluid.
- To develop compact pipe heat exchanger model and validation on CFD model will be carried out with comparison of previous experimental model.
- Effect of nanofluid in compact heat exchanger, thermal characteristics is analyzed by parameters such as the Heat transfer rate, and Thermal conductance.
- Calculating the effects of various volume concentrations of nanoparticles present in the nanofluid and their effects on heat transfer.

III. COMPUTATIONAL MODEL

The geometry of straight-square compact heat exchanger using nanofluids performing the simulation study is taken from the one of the research scholar's **A.P.C. Sarmiento et al. (2020) [26]** with exact dimensions.

Table 1 Design parameters of the compact heat exchanger

Parameter	Hot side	Cold side
Channel pitch(mm),b	3	3
Channel width(mm),w	3	3
Intermediate plate thickness(mm),a	1	1
Fin thickness(mm),e	1.5	1.5
Hydraulic diameter(mm),D_h	3	3
Number of layers	9	9
Core width (mm), W	88	88
Core height (mm), H	72	72
Pure counter flow length(mm),$L_{counter}$	210	--------
Total flow length of the plate(mm),L	363	344
Entrance Length(mm), L_{inlet}	23	0
Exit Length(mm), L_{out}	23	0

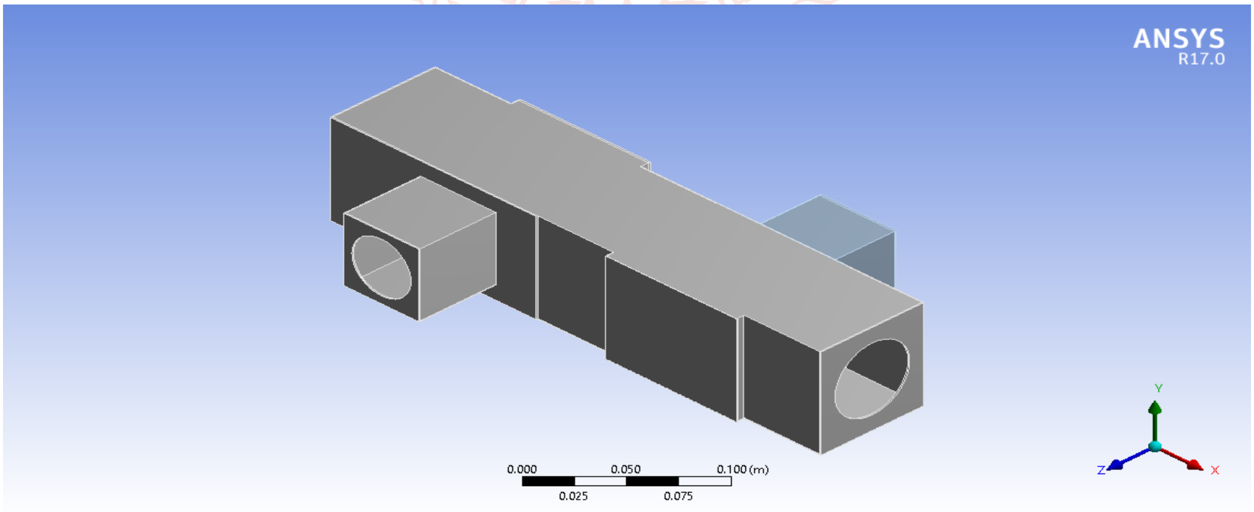

Figure 2 Solid model of compact heat exchanger

- The CFD analysis of the heat exchanger is performed in the ANSYS Fluent module.
- The solid model of the heat exchanger is created in design modular.

In the pre-processor step of ANSYS FLUENT R17.0, a three-dimensional discretized model of compact heat exchanger was developed. Although the styles of grids are connected to simulation performance, the entire structure is discretized in the finite volume of Quadcore tetrahedral grids in order to reliably calculate the thermal characteristics of compact heat exchanger using correct grids.

Table 2 Meshing details

The applied design	Number of nodes and elements
Compact heat exchanger	267155 and 804078

IV. NUMERICAL PROCEDURE

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.

4.1. Governing equations

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. The governing equations for mass, momentum, energy, turbulent kinetic energy and turbulent energy dissipation are expressed as follow,

Mass:

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0$$

Momentum:

$$\frac{\partial(\rho u_i u_k)}{\partial x_i} = \frac{\partial\left(\mu \frac{\partial u_k}{\partial x_i}\right)}{\partial x_i} - \frac{\partial p}{\partial x_k}$$

Energy Equation:

$$\frac{\partial(\rho u_i t)}{\partial x_i} = \frac{\partial\left(\frac{K}{Cp}\frac{\partial t}{\partial x_i}\right)}{\partial x_i}$$

In this project, k- ε model of renormalization group (RNG) was introduced since the estimation of near-wall flows and flows can be enhanced with a high streamline curvature. In the enhanced RNG k- ε model wall thermal effect equations, the thermal effect parameter was chosen.

Turbulent kinetic energy:

$$\frac{\partial(\rho K)}{\partial t} + \frac{\partial(\rho u_i K)}{\partial x_i} = \frac{\partial\left(\alpha_k \mu_{eff} \frac{\partial k}{\partial x_j}\right)}{\partial x_j} + G_k + \rho\varepsilon$$

Turbulent energy dissipation:

$$\frac{\partial(\rho \epsilon)}{\partial t} + \frac{\partial(\rho u_i \varepsilon)}{\partial x_i} = \frac{\partial\left(\alpha_\varepsilon \mu_{eff} \frac{\partial \varepsilon}{\partial x_j}\right)}{\partial x_j} + C_{1\varepsilon}\frac{\varepsilon}{k}G_k + C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}$$

Where, G_k represents the generation of turbulent kinetic energy due to the mean velocity gradient and

$$\mu_{eff} = \mu + \mu_t$$

$$\mu_t = C_u \rho \frac{k^2}{\varepsilon}$$

The empirical constants for the RNG k-ε model are allotted as following:

$C_{1\varepsilon} = 1.42$
$C_{2\varepsilon} = 1.68$
$\alpha_\varepsilon = 1.39$

Table 3 Thermodynamic Properties of water, air, and nano-particles

Input Parameters	Symbols	Water	Air	Al_2O_3	Units
Specific heat capacity	c_{ph}	4182	1006.43	750	J/kg-K
Density	ρ	998	1.225	3970	(kg/m^3)
Thermal conductivity	k	0.598	0.0242	46	W/m-K

Here the effective properties of the Al_2O_3/water nanofluid are defined as follows:**Pak and cho** [27], **Patel** [28] and **Ebrahmnia- Bajestan** [29] suggested the below equations for determining density, thermal conductivity, specific heat and viscosity of nanofluids.

$$\rho_{nf} = \emptyset_p \rho_p + (1 - \emptyset_p)\rho_{bf}$$

$$(\rho C_p)_{nf} = (1 - \emptyset_p)(\rho C_p)_{bf} + \emptyset_p(\rho C_p)_p$$

$$K_{nf} = K_{bf}\left\{\frac{K_p + 2K_{bf} - 2\emptyset_p(K_{bf} - K_p)}{K_p + 2K_{bf} + \emptyset_p(K_{bf} - K_p)}\right\}$$

$$\mu_{nf} = \frac{\mu_{bf}}{(1-\emptyset)^{2.5}}$$

Table 4 Thermodynamic Properties of Al_2O_3/water based nanofluid

Concentration (% by weight)	Density (kg/m³)	Specific heat (J/kg-K)	Thermal Conductivity (W/m-K)	Dynamic viscosity (Pa-s)
0.4	1000.364	4170.10	0.598	0.00103
0.8	1002.728	4158.267	0.599	0.00102
1.2	1005.092	4146.48	0.600	0.00103

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 5.5. Consolidates the restricting constraints on operating heat exchanger fluids. The input data are the inlet temperatures, pressures, and flow rate. The heat exchanger works in a counter-flow configuration.

Table 5 Details of boundary conditions

Detail	Boundary Type	Value	Remarks
Inlet-Air	Velocity inlet	4,8 and 12 m/s	Hydraulic diameter=0.03m and Turbulent intensity=3%
Inlet-Working fluid (water + Nanoparticles at different concentration)	Mass flow rate inlet	0.89 kg/s	Hydraulic diameter=0.03m and Turbulent intensity=3%
Outlet	Pressure outlet	0 Pa (gauge)	3% Turbulent intensity with Hydraulic diameter
Inner surfaces, etc.	Standard wall	Coupled	Coupled between solid and fluid
Outer surfaces	Standard wall	Heat flux=0	Insulated

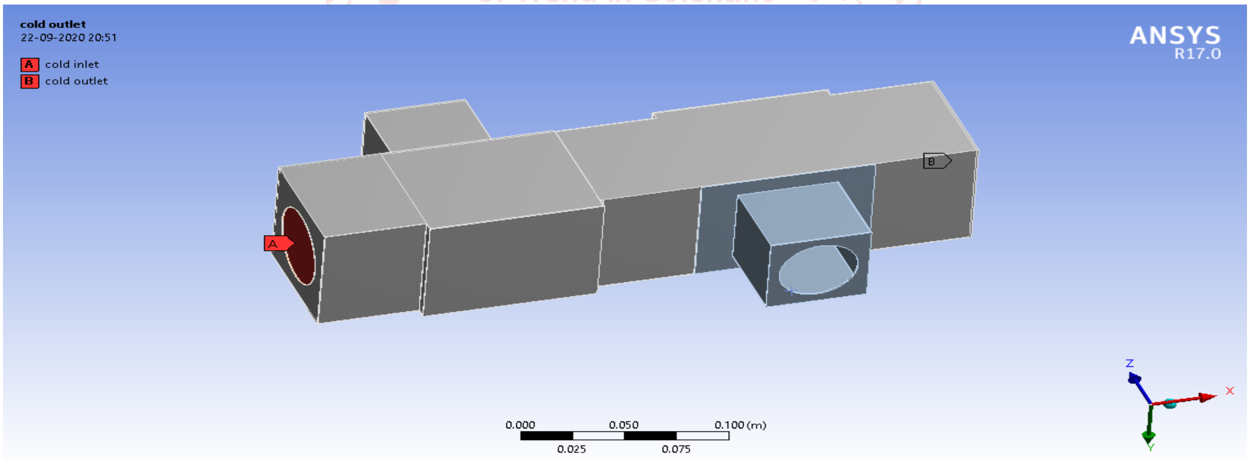

Figure 3 Inlet and outlet of the cold fluid stream of compact heat exchanger

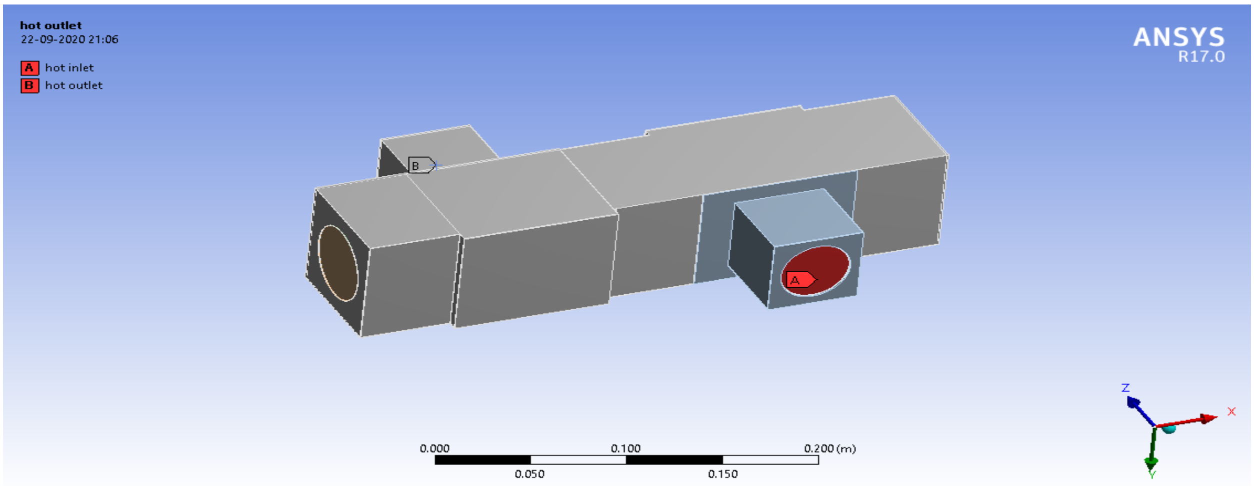

Figure 4 Inlet and outlet of the hot fluid stream of compact heat exchanger

The inlet temperature of the cold fluid stream 29.94, 31.93, and 44.53°C for the velocity 4, 8 and 12 m/s respectively. While the inlet temperature of the hot fluid stream 70°C.The solution is initialized and iterated after putting the boundary conditions in a curve line map such that the value of all parameters is visible. After the iteration gets completed final outcome may be observed.

V. RESULTS AND DISCUSSIONS

This section is aimed at evaluating the compact heat exchanger thermal performance using nanofluids. The variations in the Heat transfer rate, and Thermal conductance are measured at different numbers of the mass flow rate in order to research the performance of the compact heat exchanger using nanofluids subject to flow.

6.1. Validation of numerical computations

To validate the accuracy of developed numerical approach, comparison was made with the work reported in **A.P.C. Sarmiento et al. (2020) [26]**. The compact heat exchanger geometry that used for validation of numerical computations was considered to be as same as the geometry shown in Fig. 5.1.So, to obtain the heat transfer and the overall thermal conductance of the straight square compact heat exchanger. The hot stream and air velocity conditions are as follows:

Table 6 Shows the hot stream and cold stream test conditions

Air center line velocity (in m/s)	Cold mass flow rate (in kg/s)	Cold inlet temperature (in ˚C)	Hot mass flow rate (in kg/s)	Hot inlet temperature (in ˚C)
4	0.0308	29.94	0.894	69.69
8	0.0551	31.93	0.893	69.52
12	0.0795	44.53	0.887	69.68

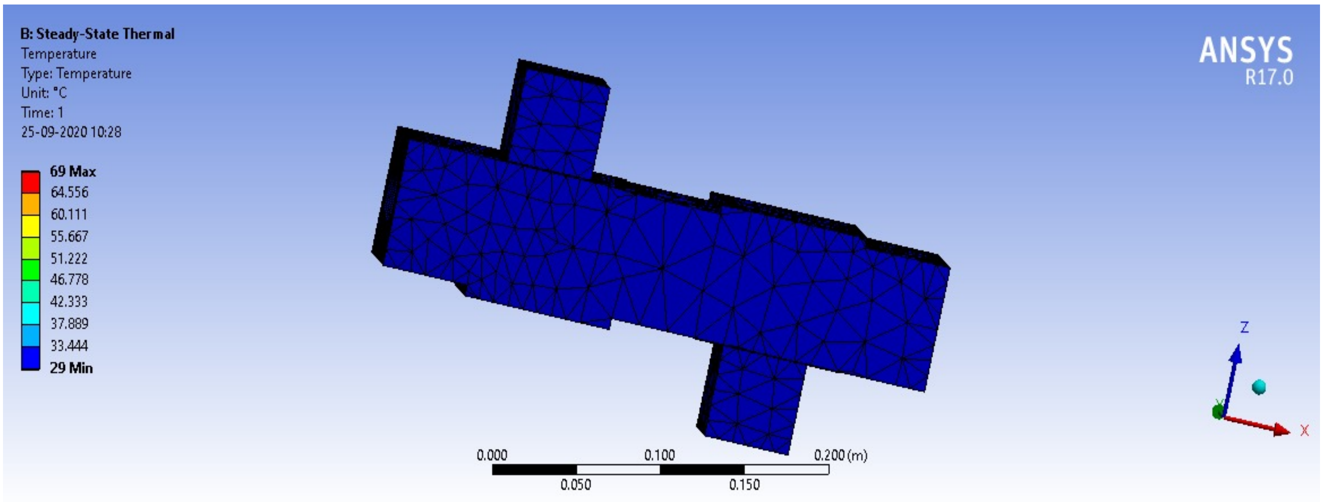

Figure 5 Static temperature contour calculated from the CFD modeling for straight square compact heat exchanger

The values of Heat transfer rate, and Thermal conductance 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 **A.P.C. Sarmiento et al. (2020) [26]**.

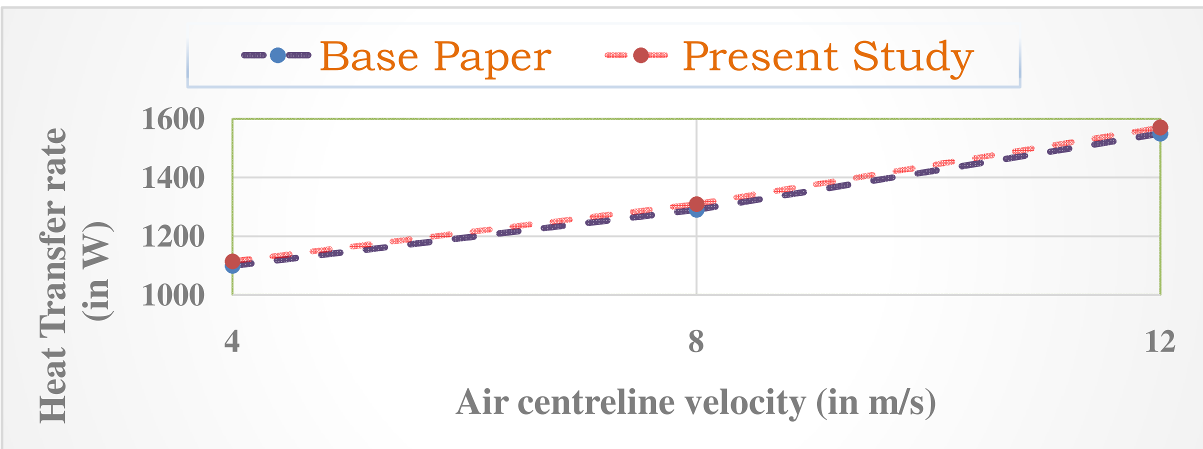

Figure 6 Heat transfer rate calculated from the CFD modeling compared with the values obtained from the analysis performed by A.P.C. Sarmiento et al. (2020) [26] for straight square compact heat exchanger

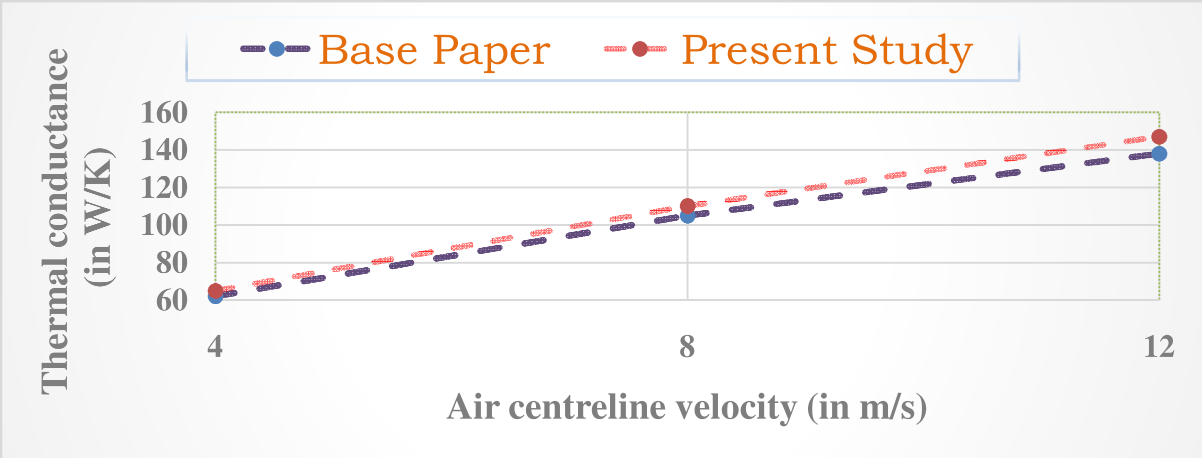

Figure 7 Thermal conductance calculated from the CFD modeling compared with the values obtained from the analysis performed by A.P.C. Sarmiento et al. (2020) [26] for straight square compact heat exchanger

From the above validation analysis it is found that the values of Heat transfer rate, and Thermal conductance calculated from CFD analysis is close to the values of Heat transfer rate, and Thermal conductance obtained from the base paper. So here we can say that the CFD model of straight square compact heat exchanger is correct.

6.2. Effect of suspension of nano-particles in the working fluid of straight square compact heat exchanger

After analyzing water as a working fluid in Straight Square compact heat exchanger, nano fluid were used as a fluid in place of pure water. In order to analyze the effect of different concentrations of nano particles on heat transfer rate, and thermal conductance, here in this work we have considered nano fluid that is aluminum oxide (Al_2O_3).Three volume fraction of nano particles that is 0.4%, 0.8%, and 1.2% in the working fluid i.e. water is suspended. The boundary conditions were same as considered during the analysis of water in Straight Square compact heat exchanger. The thermal properties of nano fluids is mention in section IV, for calculating the effect of different nano particles on heat transfer rate, and thermal conductance.

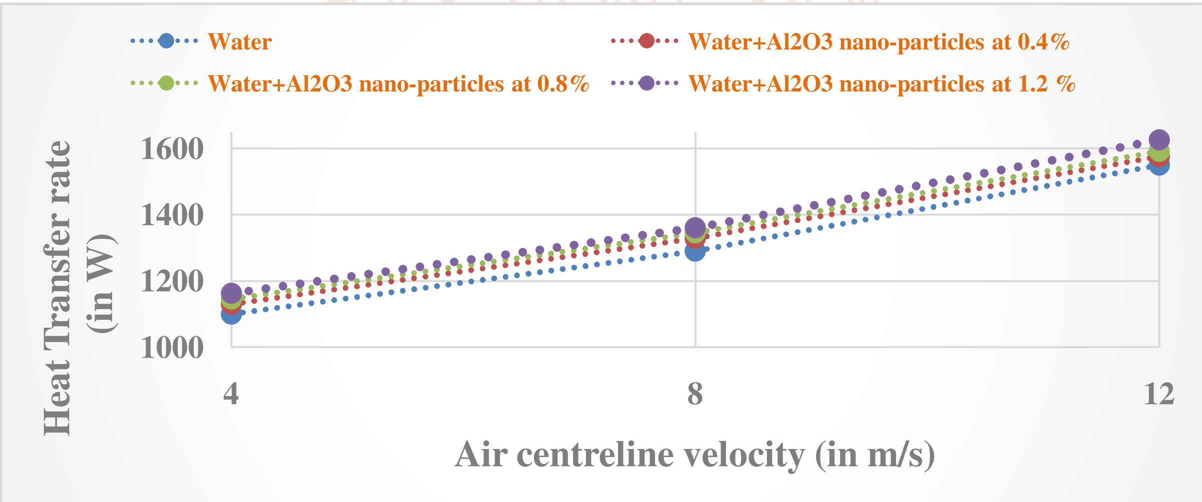

Figure 8 Heat transfer rate calculated from the CFD modeling for water/ Al_2O_3 nanofluid and compared with existing work for water as working fluid in a Straight Square compact heat exchanger

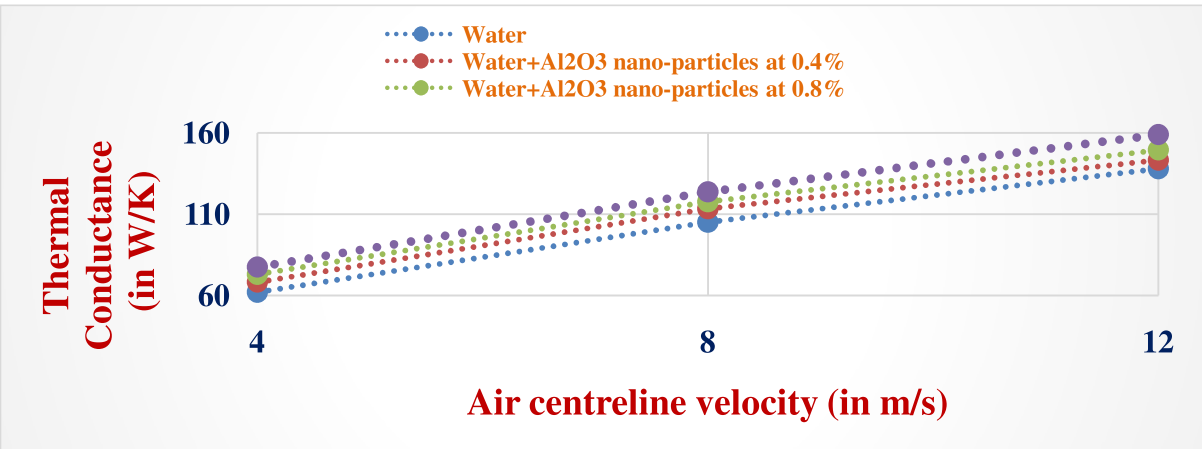

Figure 9 Thermal conductance calculated from the CFD modeling for water/ Al_2O_3 nanofluid and compared with existing work for water as working fluid in a Straight Square compact heat exchanger

VI. CONCLUSIONS

The following conclusions can be drawn based on the provided results:

- The addition of nanoparticles to the base fluid increased the coefficient of heat transfer due to the increasing heat flux.
- There is an important effect of the air centerline velocity on the improvement of the heat transfer of both the base fluid and the nanofluid.
- The thermal conductivity of the Al_2O_3 / water nanofluid improved with an increase in the weight fractions of nanofluids. Al_2O_3 / water nanofluids had the highest increase in thermal conductivity at wt. proportion = 1.2 %.
- From analysis it is found that the value of heat transfer and overall thermal conductance is higher in case of Aluminum oxide (Al_2O_3) nano-particles at 1.2 % volume fraction in water.
- In the Straight square compact heat exchanger with Al_2O_3 / water nanofluid, the thermal conductance are approximately 29% higher in comparison with the conventional fluid i.e. water.
- In the Straight square compact heat exchanger with Al_2O_3 / water nanofluid, the heat transfer are approximately 35 % higher in comparison with the conventional fluid i.e. water.
- It is also found that as the volume fraction of nano particles increases the heat transfer rate of heat exchanger also increases.
- So in this work we can say that compact heat exchanger having 1.2 % volume fraction of Al_2O_3 nanoparticles in water at different air centerline velocity shows maximum heat transfer and thermal conductance.

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