

# Study of heat and fluid characteristics of Al<sub>2</sub>O<sub>3</sub> nanofluid in a concentric tube heat exchanger fitted with a peripherally cut spiral tape of different geometrical shapes

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## Abstract

This paper presents a comprehensive numerical investigation into the heat transfer characteristics of a concentric tube heat exchanger fitted with simple and modified spiral tape inserts. The study employs Al<sub>2</sub>O<sub>3</sub> nanofluid with different concentration rates. The simulations are carried out using ANSYS Fluent software. The research begins with the validation of simulations using twisted tape inserts, aligning the results with an experimental benchmark. Subsequently, grid independence analyses are performed for the simple spiral tape and four other variations of modified spiral tape inserts.

The study then delves into the impact of various parameters on heat transfer enhancement enabled by the spiral tape inserts. Through the utilization of the Design of Experiments (DOE) methodology, three key parameters—namely, cut dimension, gap between the tube and the spiral surface, and inlet velocity—are systematically varied to identify their optimal values. With these optimized parameters established, investigations encompass three different pitch values for the tape inserts, followed by an exploration of three distinct nanofluid concentrations to identify the most effective concentration.

**Keywords:** Heat transfer, concentric tube heat exchanger, nanofluid, spiral inserts, design of experiment.

## 1. Introduction

The continuous pursuit of enhanced thermal performance in various industrial applications has driven significant advancements in heat transfer improvement techniques. Researchers have explored numerous methods, broadly categorized into two clusters: passive and active augmentation techniques. Passive techniques involve incorporating additional mechanical components, such as fins or altered tube configurations like twisted tape, into the heat exchanger [1]. On the other hand, active methods entail supplying external energy by incorporating electroactive materials or nanofluid materials [2]. Both approaches offer unique advantages and applications, contributing to the optimization of heat transfer processes in diverse industries. By understanding the principles and benefits of these methodologies, researchers and engineers can make informed decisions to enhance heat transfer efficiency in their respective fields [3].

The active method requires external power input to improve heat transfer but has limited potential due to complex designs. Additionally, supplying external power is challenging in many applications. Examples of active methods include inducing pulsation using cams and reciprocating plungers, or using a magnetic field to disturb particles in a flowing stream. In contrast, the passive method doesn't need external power and instead utilizes available system power, resulting in a fluid pressure drop. The heat exchanger industry aims to enhance thermal contact (heat transfer coefficient) and reduce pumping power to improve thermohydraulic efficiency [4].

The insertion of twisted tape elements within tubes has proven to be an effective technique for augmenting heat transfer in fluid flow. Twisted tape is a passive augmentation technique used in various applications, including heat exchangers and fluid flow systems [5]. It involves inserting a twisted tape element into a pipe or tube to enhance heat transfer or fluid dynamics. Twisted tape provides advantages over other passive techniques by enhancing heat transfer, improving energy efficiency, offering a compact design, and being versatile. It is easy to install, requires minimal maintenance, and reduces fouling, making it a cost-effective solution for various applications. The twisting of the tape creates a swirling motion of the fluid, causing it to mix more vigorously. This turbulence promotes better heat transfer between the fluid and the surrounding tube wall, resulting in improved convective heat transfer coefficients. The increased heat transfer is beneficial in applications where efficient heat exchange is desired, such as in cooling systems, refrigeration units, and industrial processes.

Various researchers have explored different designs of twisted tape to enhance the heat transfer rate, but further improvements are still required in this area. Salman et al. [6] studied heat transfer characteristics in a circular pipe using twisted tape-type horizontal baffles. They found that increasing the Reynolds number and decreasing the twist

ratio (length of one twist/twist diameter) can enhance the Nusselt number. Heat transfer was notably improved with twisted tape ratios equal to 2.93. Erdemir et al. [7] demonstrated that using dual twisted tapes leads to enhanced heat transfer and pressure drop, achieving a maximum enhancement efficiency of approximately 27% at Reynolds numbers close to 3920. Krishna Varma et al. [8] employed CFD analyses to optimize heat transfer with cut twisted tape inserts. Their results indicated increased vorticity and turbulent flow, leading to higher Nusselt numbers and heat transfer coefficients. Mashoofiet al. [9] investigated the impact of twisted tapes on the thermal performance of double pipes used for heat exchange.

In [10] Numerical methods were used to analyze various cases of using twisted tape inserts in heat exchanger pipes. The study focused on the effects of NTTI (Number of Tape Twists per Insertion) and NTT (Number of Twisted Tapes) on thermal behavior, pressure drops, and flow field. Numerical and experimental results showed good agreement and it concluded inserting twisted tape improved thermal performance, positively influencing the system. Another passive method involves adding solid particles to heat transfer fluids. Commonly used fluids like water, ethylene glycol, and oil suffer from the limitation of low thermal conductivity, which hinders their heat transfer performance. To overcome this drawback, a straightforward approach is to increase the thermal conductivity of these fluids. This idea was first proposed by Maxwell in 1873 [11], suggesting the addition of solid particles to enhance thermal conductivity. Later in 1995, Choi [12] introduced the concept of nanofluids, which refers to a mixture of liquid and tiny solid particles with diameters below 100 nm. Over the last two decades, extensive research has focused on investigating nanofluids, examining their thermophysical properties, as well as their thermal and flow performance.

Numerous pieces of evidence have emerged, indicating that nanofluids can indeed improve heat transfer performance to varying degrees, primarily due to the enhanced thermal conductivity achieved by incorporating solid nanoparticles. Additionally, other mechanisms such as Brownian motion and thermophoresis also contribute to the overall heat transfer enhancement [13].

CFD is a powerful numerical tool that allows us to simulate and analyze complex fluid flow and heat transfer phenomena. By using CFD, we can gain valuable insights into the behavior of the twisted tape and hybrid nanofluid system, which would be challenging or impossible to obtain through traditional experimental methods alone.

This study focuses on the numerical investigation of heat transfer and pressure drop within a heat exchanger employing spiral tape inserts featuring innovative geometric cuts, in combination with an AL<sub>2</sub>O<sub>3</sub>/water nanofluid, under turbulent flow conditions. The key parameters examined encompass the Reynolds number of the flow, volume fraction of nanoparticles, various geometric cut designs, and the pitch ratio. The outcomes are expressed in terms of Nusselt number, pressure drop, and friction coefficient. Additionally, for a concurrent assessment of heat transfer and pressure drop within the inner tube, a performance evaluation criterion (PEC) is employed.

The investigation employs ANSYS Fluent software to perform comprehensive numerical simulations. The initial validation of the simulation technique against experimental data establishes the credibility of the computational approach. Subsequent grid independence studies ensure the reliability of the simulations, paving the way for a systematic exploration of parameter effects on heat transfer enhancement using the Design of Experiments (DOE) methodology.

## 2. Thermophysical properties

The thermophysical properties of nanofluids are crucial in understanding their heat transfer behavior and overall performance. The following are some of the key thermophysical properties of nanofluids and their corresponding equations:

Density ( $\rho$ ):

The density of a nanofluid is a measure of its mass per unit volume. It can be calculated using the equation:

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

where:

$\rho$  is the density of the nanofluid,

$\rho_{bf}$  is the density of the base fluid (without nanoparticles),

$\varphi$  is the volume fraction of nanoparticles, and

$\rho_p$  is the density of the nanoparticles.

Specific Heat Capacity ( $C_p$ ):

The specific heat capacity represents the amount of heat energy required to raise the temperature of a unit mass of the nanofluid by one degree Celsius. It can be calculated as follows:

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

where:

C<sub>p</sub> is the specific heat capacity of the nanofluid,  
 C<sub>p\_bf</sub> is the specific heat capacity of the base fluid,  
 φ is the volume fraction of nanoparticles, and  
 C<sub>p\_n</sub> is the specific heat capacity of the nanoparticles.  
 Thermal Conductivity (k):

Thermal conductivity is a measure of the nanofluid's ability to conduct heat. The effective thermal conductivity of the nanofluid can be determined using the Maxwell's model:

$$k_{nf} = k_{bf} \left[ \frac{k_p + 2k_{bf} + 2(k_p - k_{bf})(1 + \beta)^3 \phi}{k_p + 2k_{bf} - (k_p - k_{bf})(1 + \beta)^3 \phi} \right]$$

where:

k is the effective thermal conductivity of the nanofluid,  
 k<sub>bf</sub> is the thermal conductivity of the base fluid, and  
 φ is the volume fraction of nanoparticles.

Dynamic Viscosity (μ):

Dynamic viscosity is a measure of the nanofluid's resistance to flow. It can be calculated using the following model:

$$\mu_{nf} = (1 + 2.5\phi)\mu_{bf}$$

where:

μ is the dynamic viscosity of the nanofluid,  
 μ<sub>bf</sub> is the dynamic viscosity of the base fluid, and  
 φ is the volume fraction of nanoparticles.

These equations provide essential insights into the thermophysical properties of nanofluids, which are essential for analyzing and predicting their heat transfer performance in various engineering applications (Table 1).

Table 1. Nanofluid thermal properties

Fluid/solid	ρ (kg/m <sup>3</sup> )	C <sub>p</sub> (J/kgK)	K (W/mK)	β xe-5	μ (kg/ms)	σ (1/ohmm)	
water	997.1	4179	0.613	21	0.001003	0.05	
Al <sub>2</sub> O <sub>3</sub>	3970	765	40	14.185			
Solution	ρ <sub>nf</sub>	C <sub>p</sub> <sub>nf</sub>	K <sub>nf</sub>	β <sub>nf</sub> xe-5	μ <sub>nf</sub>	σ <sub>nf</sub>	%nanofluid concentration
1	1001.172	4165.462	0.614759	20.97298	0.001006		0.1
2	1013.059	4112.106	0.621827	20.86647	0.001016	1013.059	0.5
3	1024.946	4059.987	0.62895	20.76243	0.001026	1024.946	0.9

### 3. Validation

In this section, we simulate the flow of γ-Al<sub>2</sub>O<sub>3</sub>/Water in a circular tube with twisted tape inserts using ANSYS Fluent software. The simulation is based on the reference article [15] which is a study on heat transfer and friction factor characteristics of γ-Al<sub>2</sub>O<sub>3</sub>/water through circular tube with twisted tape inserts with different thicknesses. The obtained results are validated against the reference article. The simulation considers a γ-Al<sub>2</sub>O<sub>3</sub>/Water fluid with an initial temperature of 300 K and a velocity of 0.716 m/s (Reynolds number = 1600-800). The fluid enters the computational domain through a multi-stage twisted circular tube, where the outer wall experiences a heat flux rate of 5000 W/m<sup>2</sup>, leading to a rise in fluid temperature. These findings will be the basis for the subsequent optimization of heat transfer efficiency using the Design of Experiment (DOE) method.

#### 3.1. Geometry

First, the geometry is created in SolidWorks software, and subsequently, Design Modeler from the ANSYS software suite is used to prepare the geometry for meshing. The meshing process and boundary conditions are defined using

ANSYS Meshing software. The geometry production involves designing a pipe with a diameter of 22 mm and a length of 2200 mm. Additionally, a complete twist has a length of 110 mm. These dimensions are used to construct the intricate geometry required for the study (Figure 1)

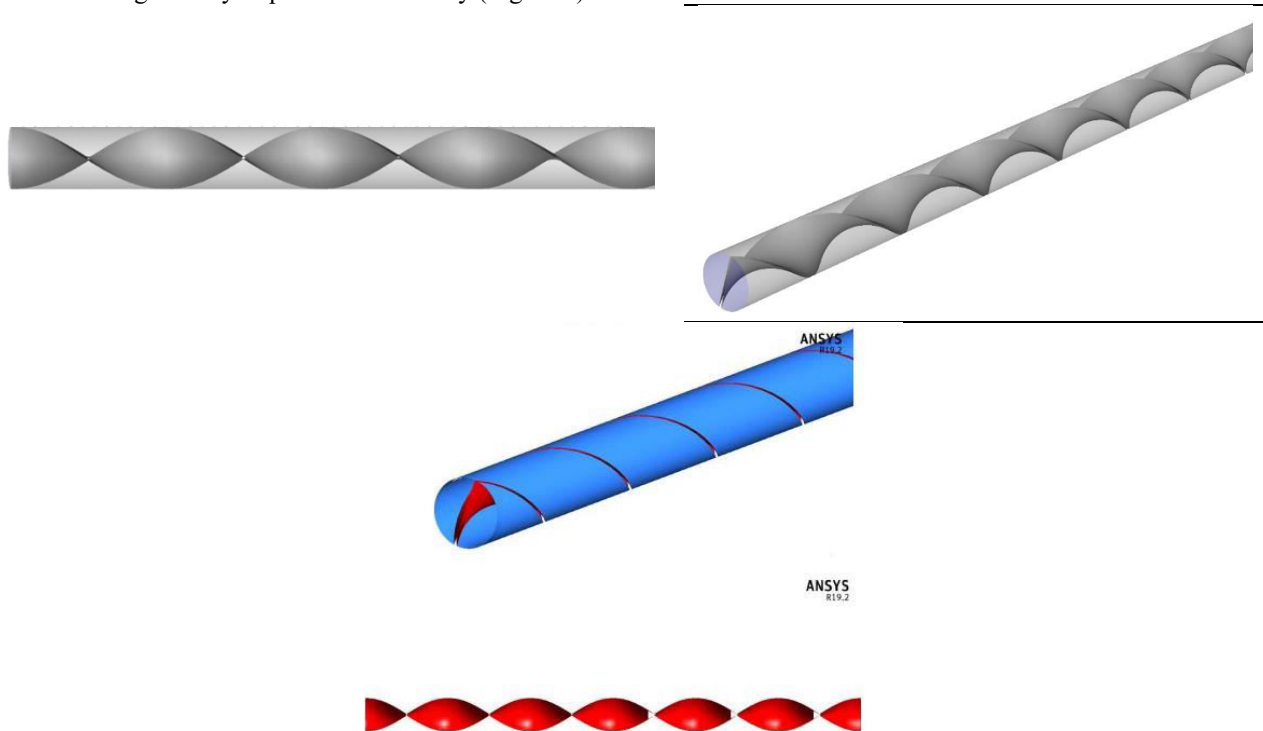


Figure 1. Geometry

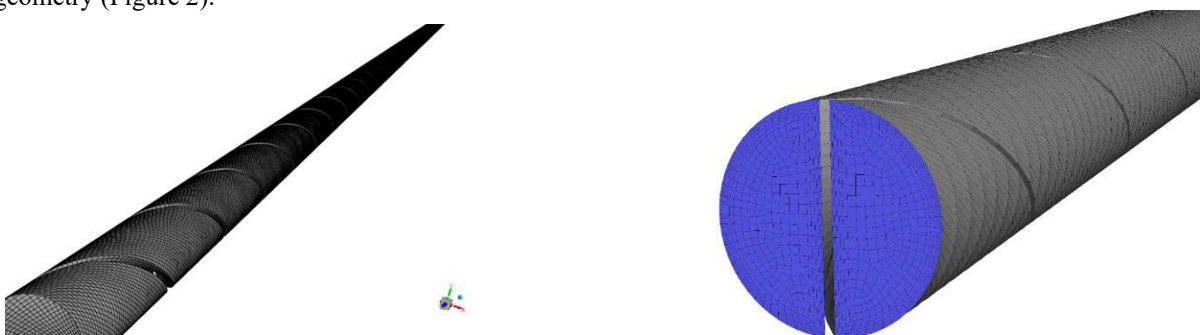
The fluid that passes through the pipe is air, the properties of which are given in the table below (Table 2)

Table 2. air properties

Material properties		Standard
Air		
	density	1.225 kg.m <sup>-3</sup>
	viscosity	1.7894e-05 Kg/m.s

### 3.2. Grid generation

In the ANSYS Meshing software, an unstructured square grid with a well-designed boundary layer is utilized for the calculations. The model comprises approximately 4 million cells, ensuring a detailed and accurate representation of the geometry (Figure 2).



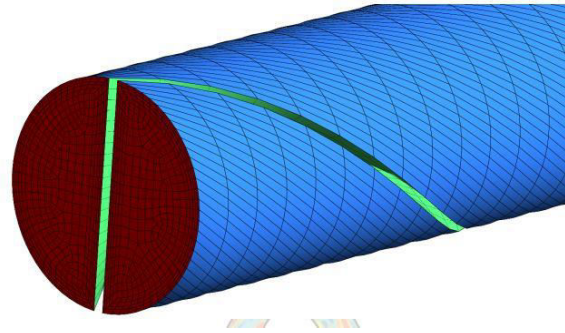


Figure 2. Computational domain

### 3.3. Simulation

To address the problem, the K-epsilon Realizable turbulence model was employed for the simulations. The coupling of the speed and pressure equations was achieved using the Coupled algorithm. The boundary conditions applied to solve the equations at a Reynolds number of 800 are summarized in the following table:

Table 3. Boundary condition of flow

$T_i$	298.15
$U_i$	0.0365
$Q_w$	3500

The solvers and methods used in this simulation are as follows:

Table 4. methods and solvers

Viscous		k-e realizable
	k-e model	realizable
	Near-wall treatment	Standard wall function

### Methods

Pressure-Velocity Coupling		SIMPLE
	Pressure	Second-order
	momentum	first-order upwind
	turbulent kinetic energy	first-order upwind
	specific dissipation rate	first-order upwind
	gradient	Least squares cell base

The simulation was conducted using the pressure-based solver in a transient (time-dependent) manner. However, for this particular problem, the effect of gravitational force was neglected during the simulation. As a result, the simulation and its results remain constant and do not vary with time.

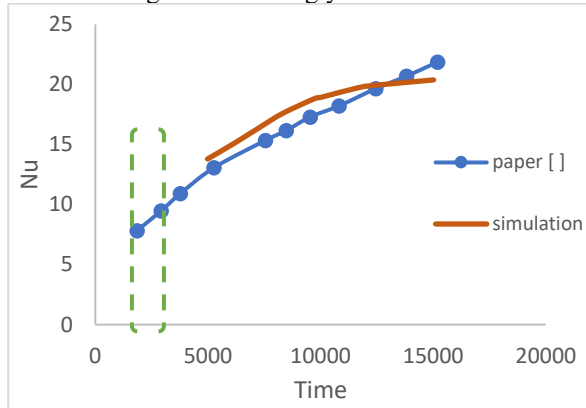
The inlet boundary condition specifies the velocity and temperature of the incoming flow based on the Reynolds number and the diameter of the inlet pipe. The boundary conditions and initial conditions for the problem are as follows:

Table 5. boundary conditions

Boundary condition		
<b>Inlet</b>		Velocity Inlet
	velocity magnitude	0.716 m/s
	Temperature	300 k
<b>Outlet</b>		Pressure Outlet
<b>wall</b>		Wall
<b>Outer Tube walls</b>	Heat flux	5000 w/m <sup>2</sup>
<b>Inner walls</b>	Heat flux	0 w/m <sup>2</sup>

### 3.4. Results

the obtained results were compared with the findings from the reference article. The comparison between the simulation results and the experimental data was conducted for Reynolds numbers of 800 and 1600. The Fluent software was configured accordingly to solve the Navier-Stokes equations for incompressible flow.



$$Re = \frac{1022.535 * 0.716 * 0.0070035}{0.001025} \approx 500$$

$$error = \frac{14.815 - 13.5}{13.5} = 0.097$$

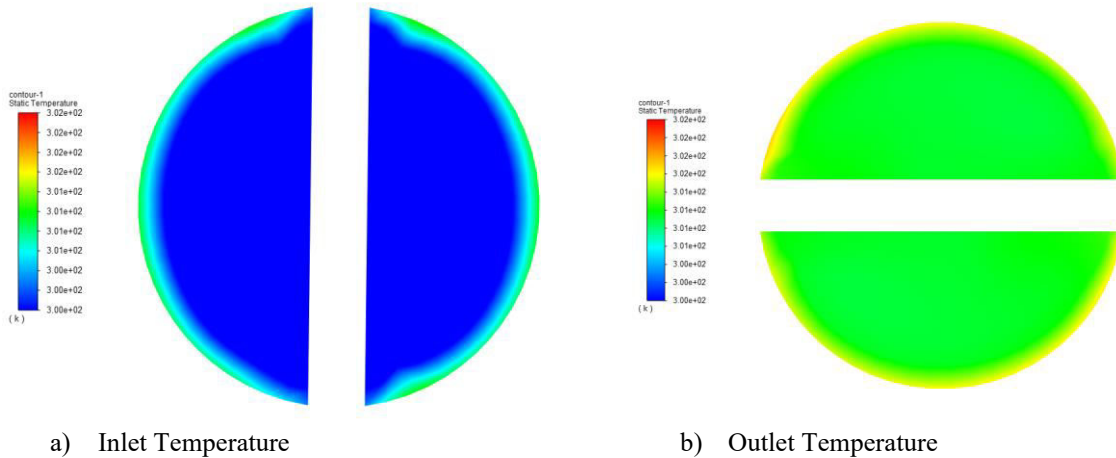
Figure 3. Comparison of Nusselt number

Upon conducting the comparison, the results of the present study were validated against the experimental data for the specified Reynolds numbers (800 and 1600). The agreement between the simulation results and the experimental findings demonstrates the accuracy and reliability of the simulation setup and the chosen numerical model.

Table 6. Validation results

REYNOLDS NUMBER		NU	E%
Re=800	experimental	24.78	1.78
	Numerical (current work)	25.23	
Re=1600	experimental	42.094	2.311
	Numerical (current work)	43.09	

As mentioned earlier, the simulation has been validated against experimental results. The contours of pressure, temperature, and velocity are presented below:



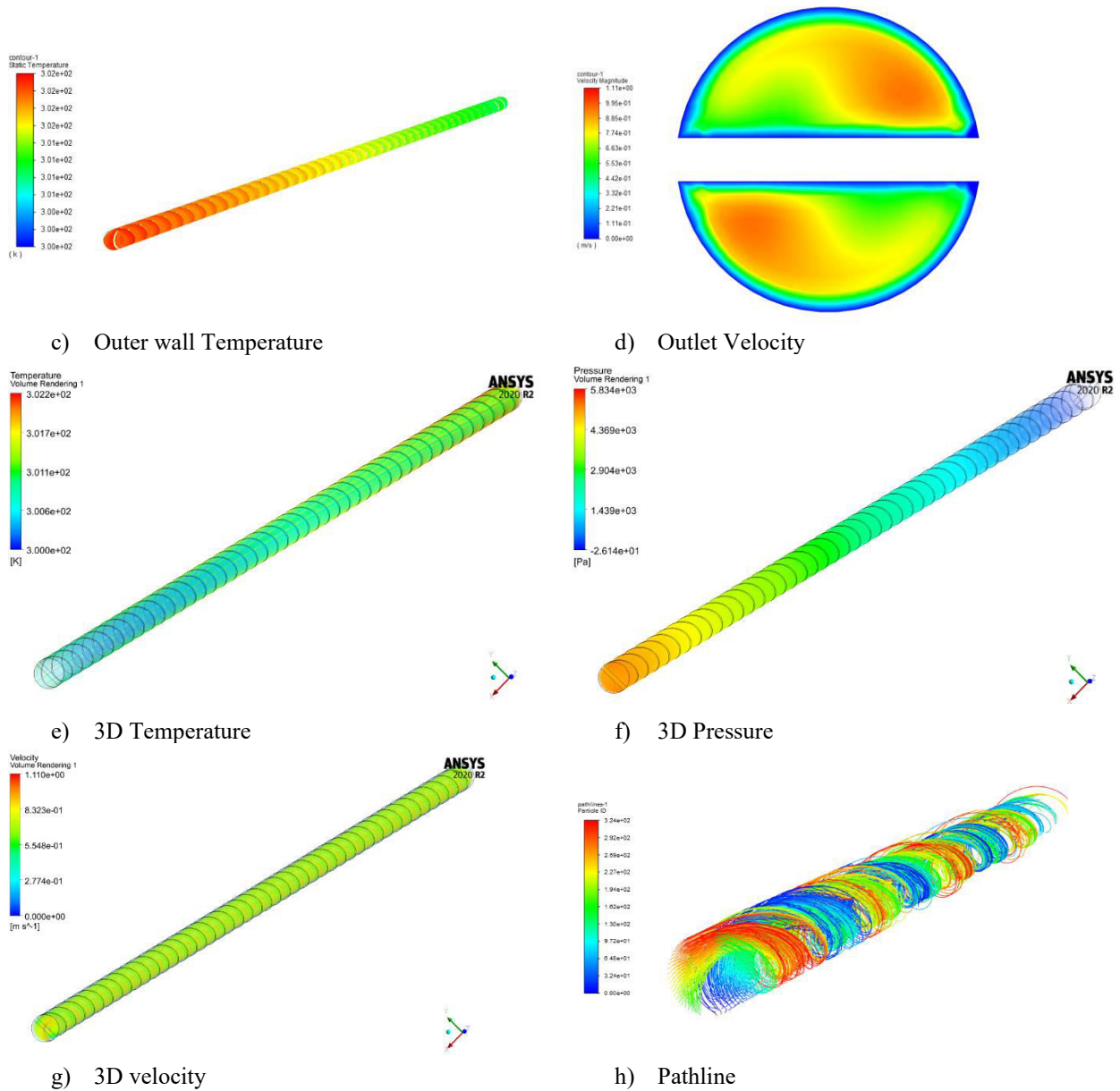


Figure 4. Contours

#### 4. Setup

The present study involves a numerical investigation into the heat transfer and pressure drop characteristics of Al<sub>2</sub>O<sub>3</sub>/water nanofluids, considering various particle concentrations. The research employs five distinct types of inserts, including a simple spiral tape (SST) and four variations of modified cut spiral tape (MST) with differing cut shapes. The simulation methods and models mirror those described in the validation section, maintaining consistent boundaries and initial conditions. The geometry of the spiral inserts is depicted in Figure (5). Notably, the tape thickness measures 0.5 mm, with a clearance of 0.25 mm. The pitch values adopted are 35 mm, 50 mm, and 65 mm for both the simple and modified spiral tape configurations.

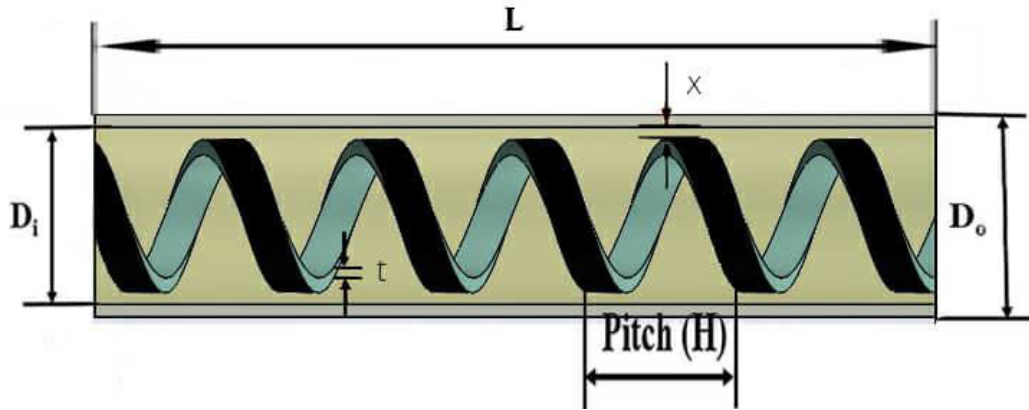


Figure 5. Schematic of simple spiral tube

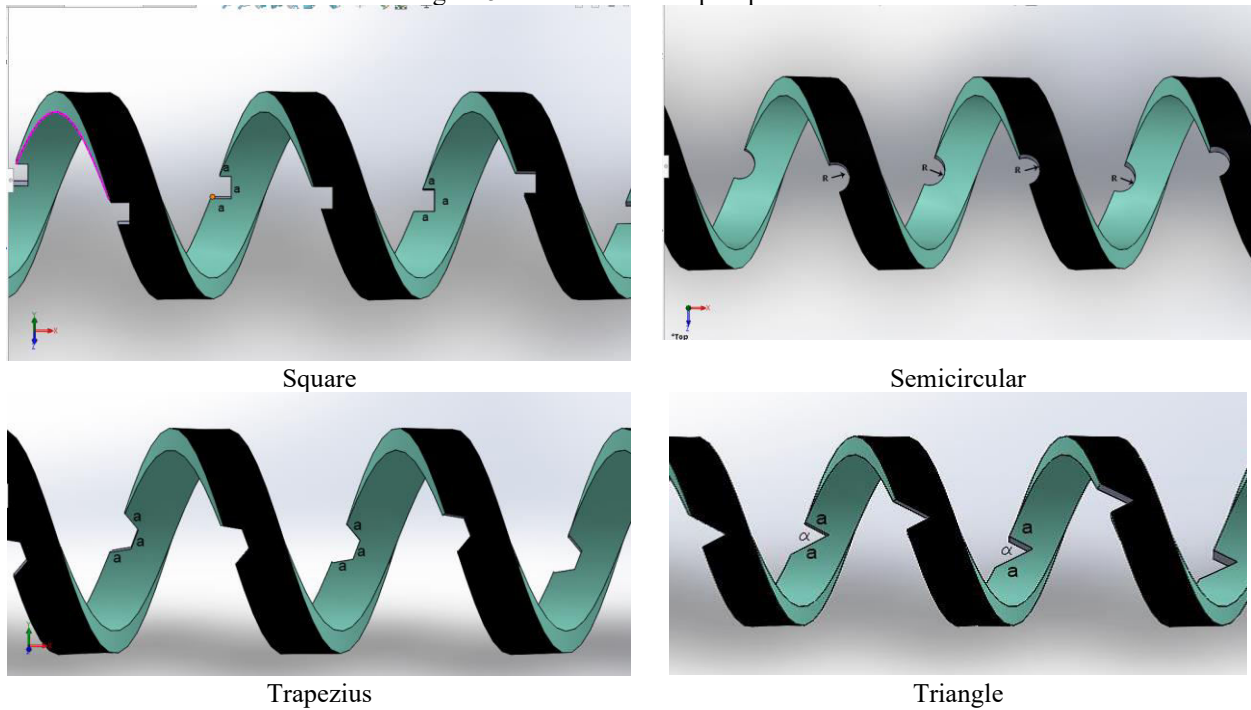


Figure 6. Different types of spiral inserts

### 5. Grid independency

At this stage, we checked grid independency using simulations with five different cut configurations. The results showed that the Nusselt number varies by less than 2 percent when the number of cells exceeds 22 million. This ensures reliable and accurate heat transfer characteristics for subsequent analyses and optimizations.

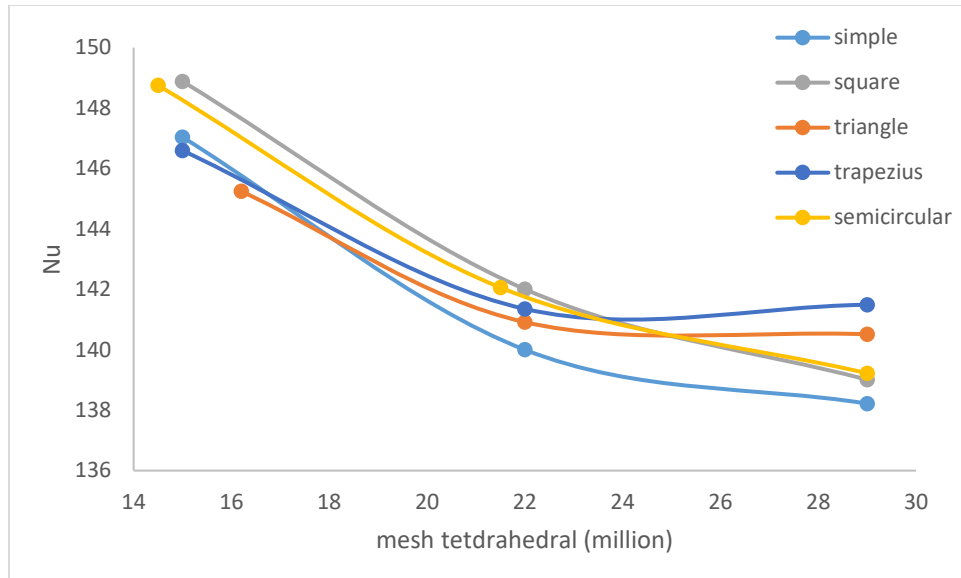
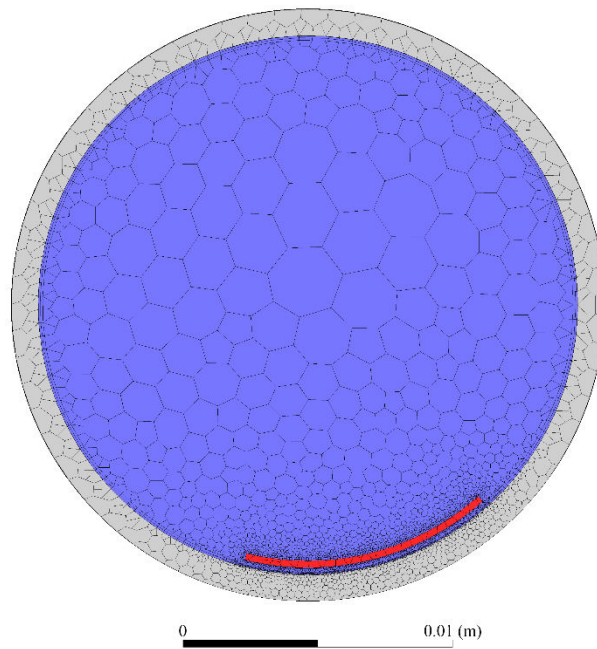


Figure 7. Mesh grid independency

Based on Figure (7), it's evident that the semicircular and square cut configurations have the highest Nusselt. As a result, these two cut configurations will be utilized for optimization in the subsequent sections.



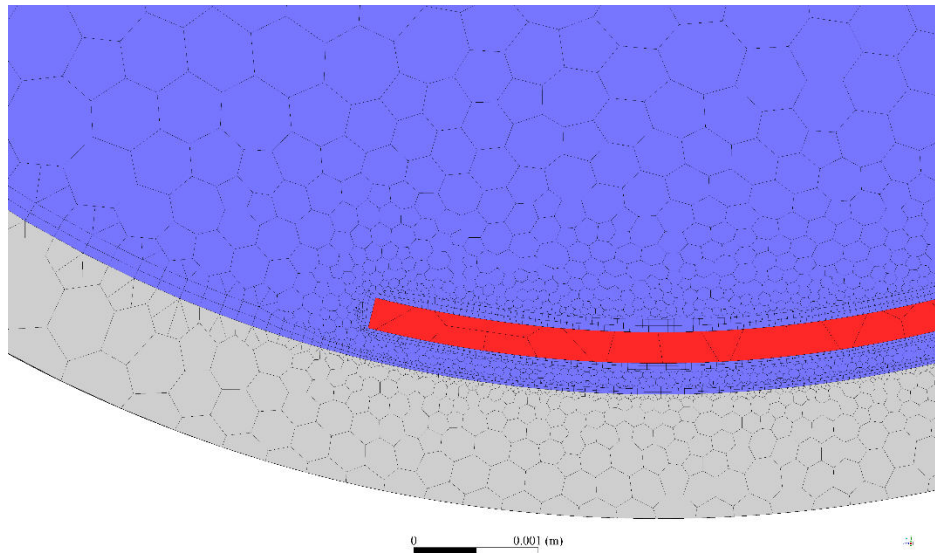
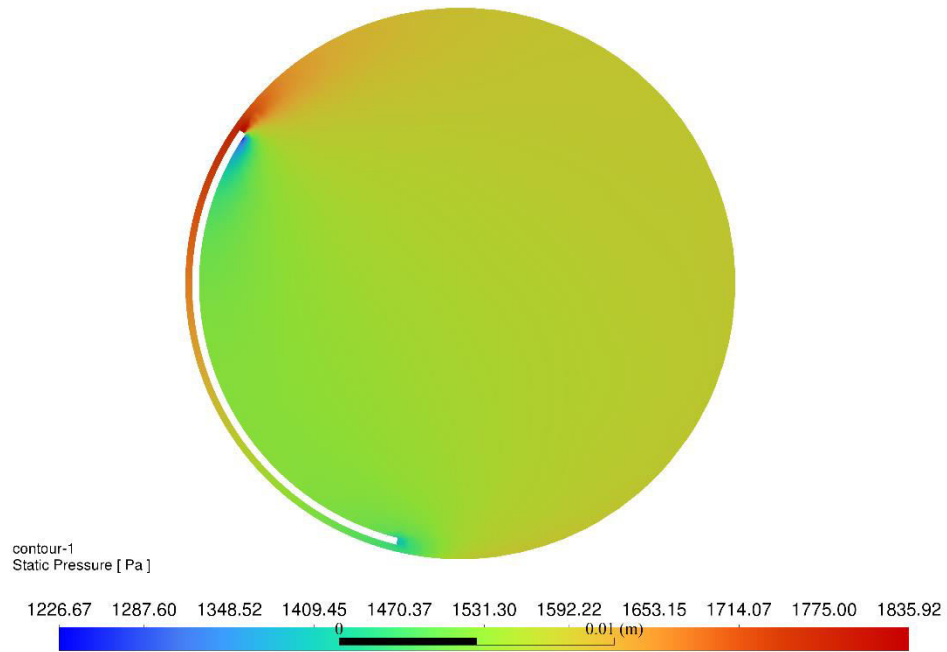


Figure 8. mesh grid

### 6. Optimization

The modeling of the circular tube with spiral tape geometry is simulated in ANSYS Fluent. The governing equations, encompassing continuity, momentum, and energy equations, are numerically solved through the finite volume method. The simulation of nanofluid flow behavior and heat transfer is conducted under diverse operating conditions.



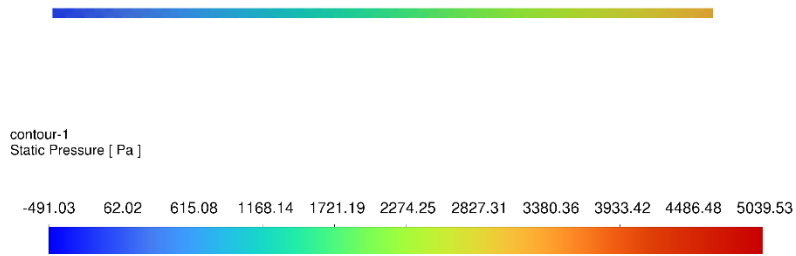
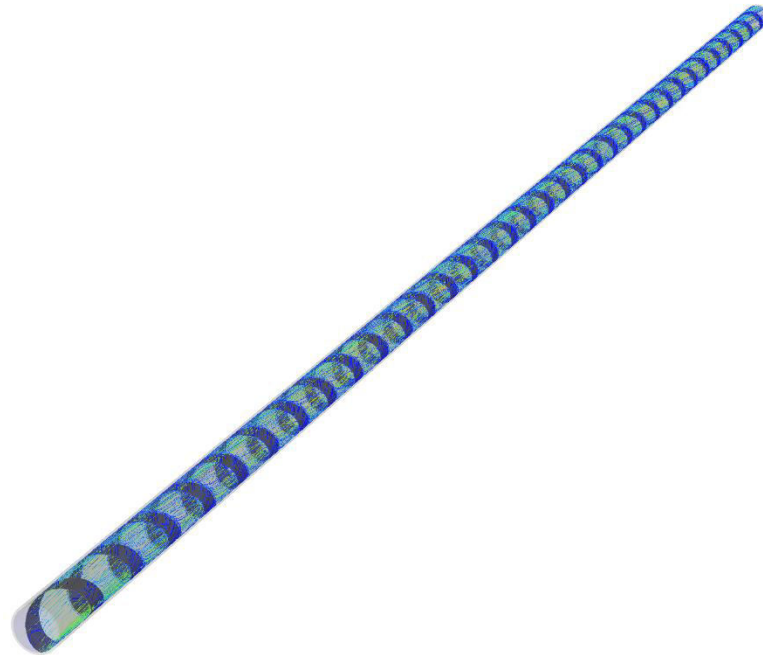
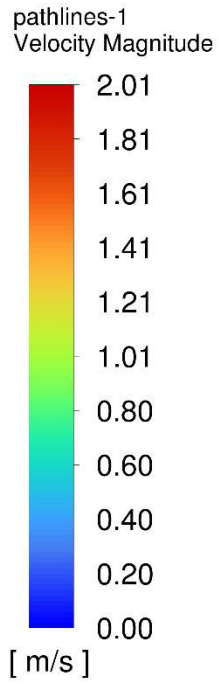


Figure 9. Static pressure contour



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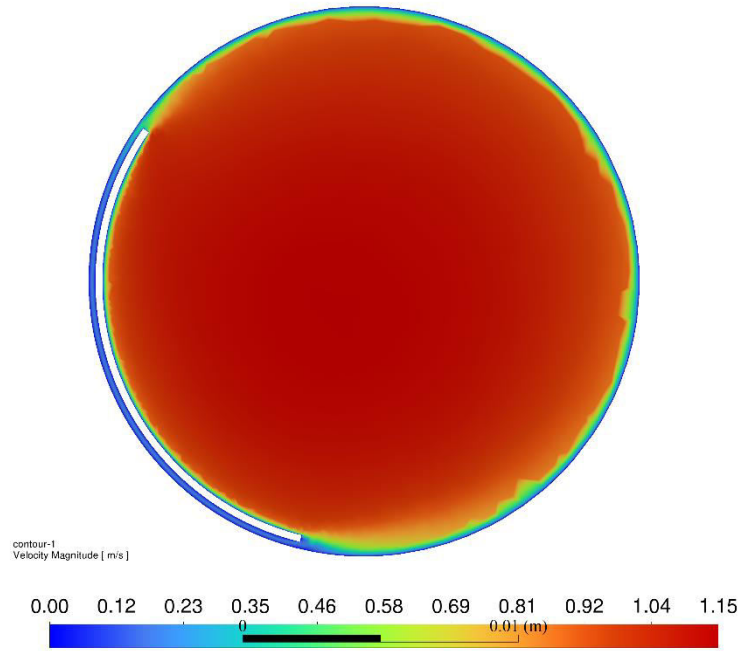
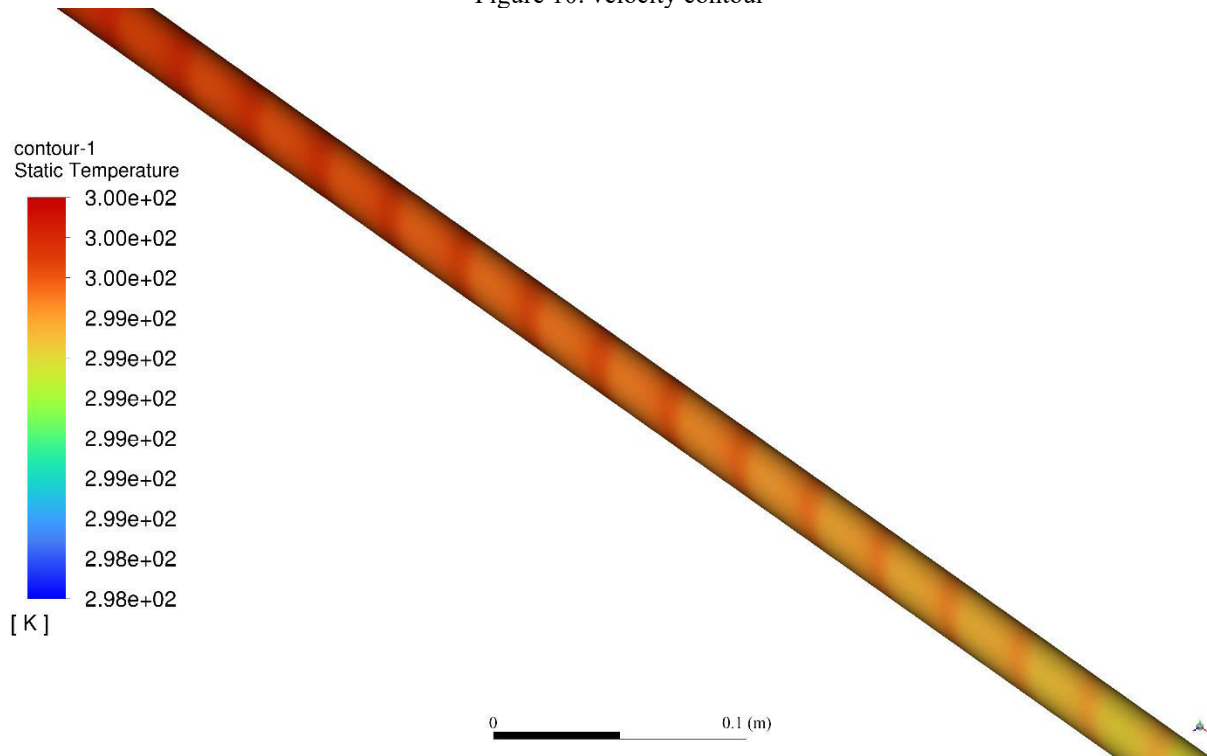


Figure 10. velocity contour



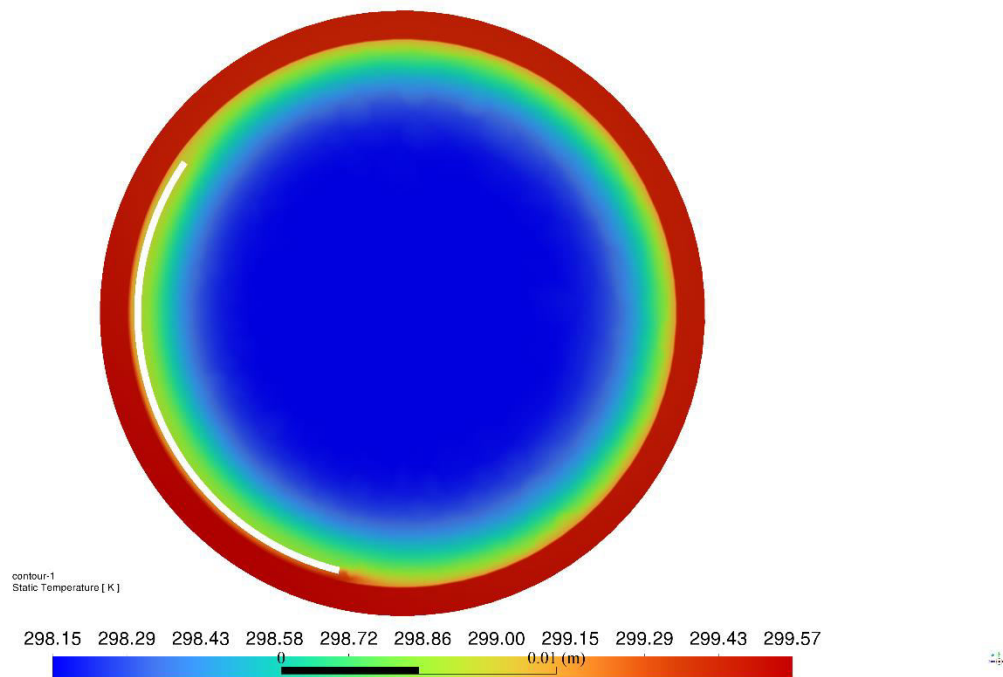


Figure 11. temperature contour

According to the pressure and temperature contours, it can be seen that the spiral tape inserts has created a small space between the tube wall and the inserts, which has decreased the speed of the fluid in these areas. In addition, it creates vortices and eddies through the flow, all of which help improve heat transfer.

To initiate the investigation, optimization of the cutting dimension, the gap between the tube and the spiral surface, and inlet velocity were performed using the Design of Experiment (DOE) method. Via DOE, the most favorable configurations for these three parameters to enhance heat transfer efficiency were systematically analyzed and identified. This analysis is carried out for cut configurations that have the highest Nusselt value, the semicircular and square cut.

Following this, the influence of pitch and nanofluid concentration was examined, considering three different values for each. These additional parameters play a crucial role in advancing the understanding and enhancement of heat transfer characteristics within the tube.

### 6.1. Design Of Experiment

In this section, an experiment to find the best values for cutting dimension, Gap, and velocity will be simulated for both semicircular and square cuts.

The initial range for the first three parameters, which are to be analyzed using the Design of Experiment (DOE) method, is outlined as follows:

- 1- Cutting Dimension Parameter: The cutting dimension parameter ranges from 0.0009 to 0.00585.
- 2- Gap Parameter: The gap parameter varies within the range of 0.25 to 1 mm. As per the geometry in the Fluent software, specific values of 0.00785 and 0.0095 are selected for the DOE table.
- 3- Velocity Parameter: The velocity value is determined by the Reynolds number, which ranges between 4000 and 30000. Within this range, the velocity is set to span from 0.2 to 1.5 m/s.

Table 7. Parameter ranges

RUN	P2 CUT (M)	P6 GAP (M)	PG VELOCITY(MS^-1)	P10 NUSSELT-1-OP
1	0.003375	0.009125	0.85	196.49
2	0.0009	0.009125	0.85	195.25
3	0.00585	0.009125	0.85	197.39
4	0.003375	0.00875	0.85	190.61
5	0.003375	0.0095	0.85	171.58
6	0.003375	0.009125	0.2	95.377
7	0.003375	0.009125	1.5	231.31
8	0.001363	0.00882	0.32153	104.22
9	0.005387	0.00882	0.32153	108.98
10	0.001363	0.00943	0.32153	103.41
11	0.005387	0.00943	0.32153	112.36
12	0.001363	0.00882	1.3785	218.32
13	0.005387	0.00882	1.3785	218.74
14	0.001363	0.00943	1.3785	228.24
15	0.005387	0.00943	1.3785	239.76

Upon the completion of these 15 simulations, the optimal value for each parameter resulting in the highest Nusselt number will be identified. Subsequently, utilizing these optimized parameter values, three distinct pitch values (18,25,39 mm) will be investigated to determine the most favorable pitch configuration. From there, using these four optimized parameters, the analysis will extend to three different concentrations of nanofluid (0.1%,0.5%,0.9%), to identify the optimal nanoparticle concentration.

**7. Results and Discussion**

The results of the Design of Experiment (DOE) for the cut, gap, and velocity parameters are summarized as follows: Based on the response surface analysis, it becomes evident that the Nusselt number rises with an increase in both the cut dimension and velocity. However, when examining the gap parameter, a distinct optimal point emerges where the Nusselt number begins to decrease as depicted in Figure (12). This observation underscores the critical role of these parameters in influencing the heat transfer characteristics within the system.

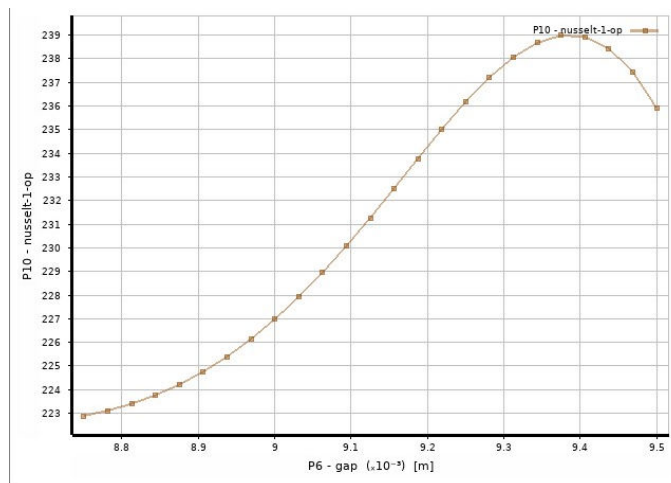


Figure 12. effect of gap parameter on the Nusselt (semicircular cut)

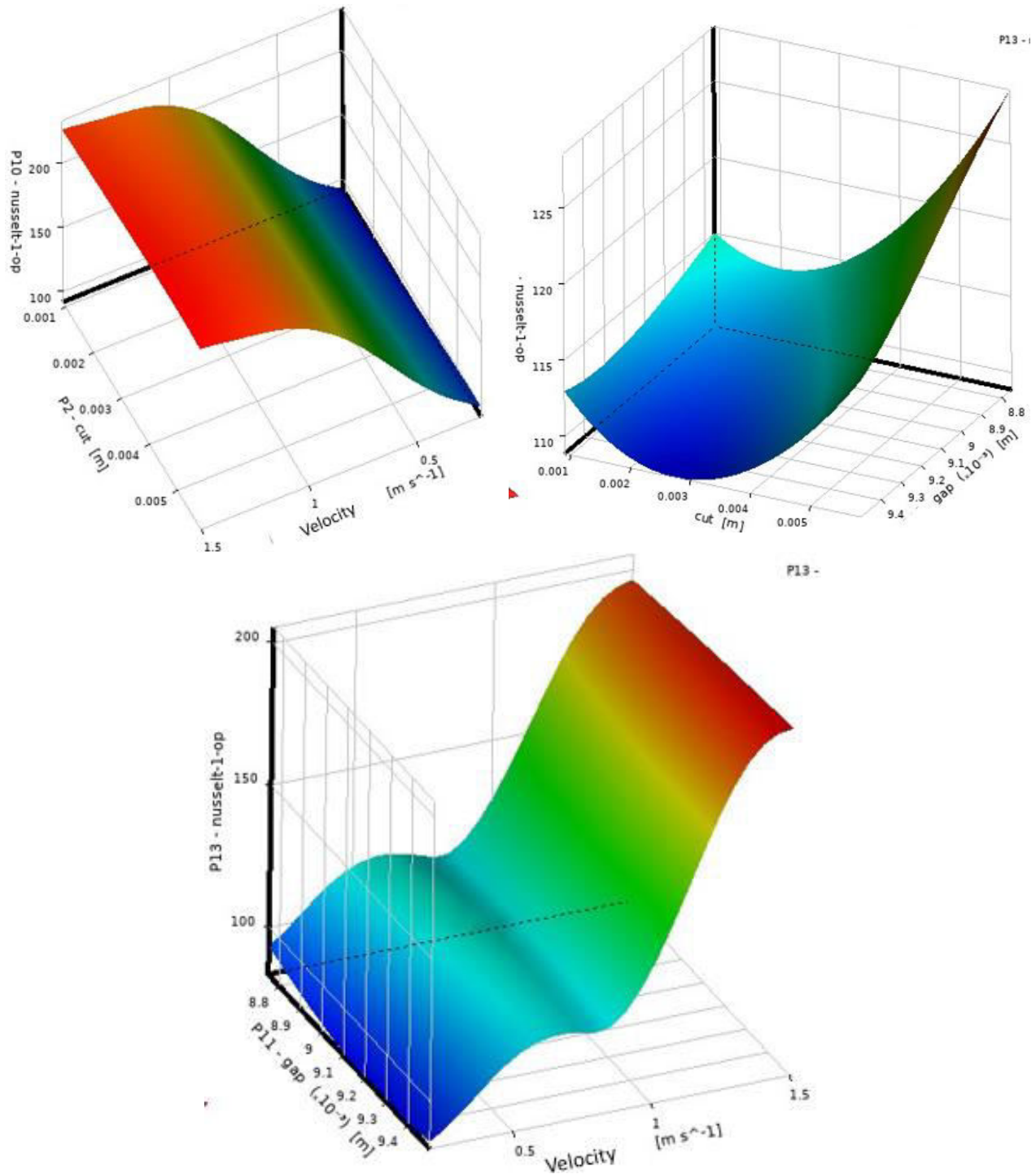


Figure13. Response Surface of DOE (semicircular cut)

Similar to semicircular cut, DOE of square cut also has been done. Response surfaces of the doe are depicted in Fig (14). It shows that Nusselt is maximized at the highest value of cut dimension and highest value of gap.

The primary objective of optimizing heat exchanger design is to enhance heat transfer while minimizing the accompanying pressure drop. To provide a comprehensive assessment of the thermal efficiency of nanofluids, previous studies on heat transfer enhancement have utilized the thermal performance factor [16,17]. In this study, performance evaluation criteria will be used as follows.

$$f = \frac{\Delta P}{\left(\frac{1}{D_i}\right) \left(\rho_f \frac{u_f^2}{2}\right)}$$

$$PEC = \frac{(Nu_{nf}/Nu_w)}{(f_{nf}/f_w)}$$

Table 8. thermal performance factor value

NUMBER SIMULATIONS	OF	NU NF	F NF	EPC
1		121.1883	0.250877	1.277797
2		82.21	3.955595	0.99301
3		200	0.088532	1.918884
4		112.1741	0.27593	1.075368
5		111.45	0.26287	1.121508
6		119.77	0.287414	1.102308
7		121.26	0.281787	1.138305
8		99.68	1.208713	1.524573
9		198.08	0.112694	1.76785
10		93.46	1.570482	1.100161
11		207.26	0.089143	2.338472
12		118.77	1.320136	1.663227
13		198.92	0.122233	1.636801
14		99.07	1.709541	1.071336
15		215.31	0.097579	2.219288

Analyzing the effect of velocity parameters also reveals that the highest velocity value provides the best heat transfer performance (see Fig (13)).By investigating the impact of these three parameters, values of 1.5 m/s for velocity, 0.0095 for gap (equivalent to 0.25), and 0.0585 m for width have been selected for further parameter studies.

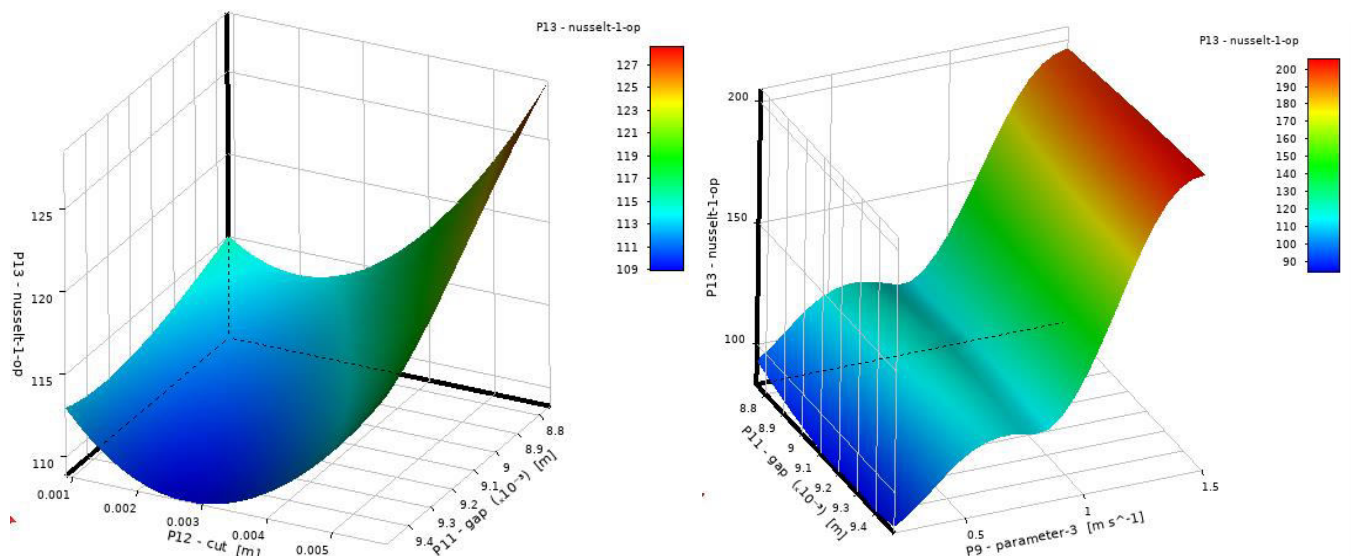


Figure 14. Response Surface of DOE (square cut)

The nanofluid parameter, as in the previous scenario, delivers the optimal results at the lowest value. Therefore, a 0.1% nanofluid concentration has been employed for these cases.

The examination of the pitch parameter indicates that the minimum allowable pitch parameter, which in this case is 0.018 meters, results in the best configuration for square grids. The NASA number for this configuration is 218,

which is lower than the value obtained in the semicircular case. Since, in the following process of optimization, the semicircular cut configuration will be considered.

For semicircular cut configuration, considering three different pitch values has led to the selection of the optimal pitch value, which is determined to be 18 mm.

	PITCH	NU
1	39	243.29
2	25	262.437
3	18	267.990

The investigation involved studying the nanofluid concentration across three different values: 0.1%, 0.5%, and 0.9%. This analysis was conducted within the context of the 18 mm pitch, which was determined to yield the most effective heat transfer performance.

	NANO FLUID	NU
1	0.1	267.990
2	0.5	263.7961
3	0.9	255.0524

The Nusselt number for the geometry used in the grid independence study was 149.41. However, after optimization, this value increased to 260.94. Notably, this optimization was achieved considering a velocity of 1 m/s during the grid independence study, whereas the optimal velocity is 1.5 m/s.

Remarkably, the optimal Nusselt number of 205, as indicated in the DOE table for a velocity of 1 m/s, gap, and cutting dimension, remains unaffected by the pitch parameter. Intriguingly, in all DOE runs, the nanofluid concentration was consistently maintained at 0.1%. This concentration holds the greatest influence, with the value of 205 persisting across various scenarios, excluding the pitch parameter.

Consequently, the semicircular spiral cut exhibits a remarkable 33% enhancement in performance. This improvement underscores the substantial impact of the optimized parameters, nanofluid concentration, and geometrical considerations on heat transfer efficiency.

## 8. Conclusion

In this study, a thorough investigation of heat transfer enhancement within a circular tube utilizing simple and modified spiral tape inserts has been conducted. The integration of nanofluids, including Al<sub>2</sub>O<sub>3</sub>/water nanofluid and a hybrid nanofluid containing Al<sub>2</sub>O<sub>3</sub> and CuO nanoparticles in water, adds an additional dimension to the research. Through rigorous simulations using ANSYS Fluent software, the following key outcomes have been achieved:

**Validation and Grid Independence:** The simulation technique has been validated against experimental data for twisted tape inserts, establishing its accuracy. Grid independence analyses ensure the reliability of subsequent investigations.

**Parameter Optimization:** By employing the Design of Experiments (DOE), optimal values for parameters like cut dimension, gap, and inlet velocity have been identified, leading to significant heat transfer enhancement.

**Nanofluid Influence:** Investigation of different nanofluid concentrations has revealed that specific concentrations offer superior heat transfer performance, both for Al<sub>2</sub>O<sub>3</sub>/water nanofluid and the hybrid nanofluid.

The results obtained from this study provide insights into the use of spiral tape inserts and nanofluids to enhance heat transfer. The optimized parameter values presented here offer valuable guidance for practical applications that aim to improve heat transfer efficiency in different industrial processes.

### Processing system

The system required 1 day on average to complete each simulation, with 128 GB of RAM available for processing. The CPU model was Intel Xenon E5-2680 v2@2.8 GHz.

### References

- [1] Dewan A, Mahanta P, Raju KS, Kumar PS. Review of passive heat transfer augmentation techniques. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy 2004;218:509–27.
- [2] Léal L, Miscevic M, Lavieille P, Amokrane M, Pigache F, Topin F, et al. An overview of heat transfer enhancement methods and new perspectives: Focus on active methods using electroactive materials. Int J Heat Mass Transf 2013;61:505–24. <https://doi.org/https://doi.org/10.1016/j.ijheatmasstransfer.2013.01.083>.
- [3] Ligrani PM, Oliveira MM, Blaskovich T. Comparison of heat transfer augmentation techniques. AIAA Journal 2003;41:337–62.

- [4] Rohsenow WM, Hartnett JP, Ganic EN. Handbook of heat transfer applications 1985.
- [5] "THE EFFECTS OF RETARDERS IN FIRE TUBES OF STEAM BOILERS." *Journal of the American Society for Naval Engineers* 1896;8:779–81. <https://doi.org/https://doi.org/10.1111/j.1559-3584.1896.tb00751.x>.
- [6] Salman SD, Kadhum AAH, Takriff MS, Mohamad AB. CFD analysis of heat transfer and friction factor characteristics in a circular tube fitted with horizontal baffles twisted tape inserts. *IOP Conf Ser Mater Sci Eng*, vol. 50, IOP Publishing; 2013, p. 012034.
- [7] Güneş S, Erdemir D, Özceyhan V, Altıntop N. Numerical Investigation Of Heat Transfer Enhancement And Pressure Drop In Heat Exchanger Tube Fitted With Dual Twisted Tape Elements. 2013.
- [8] Krishna Varma K, Srinivas Kishore P, TulasiTirupathi. CFD Analysis for the Enhancement of Heat Transfer in a Heat Exchanger with Cut Twisted Tape Inserts. *SSRG International Journal of Mechanical Engineering* 2017;146–52.
- [9] Mashoofi N, Pourahmad S, Pesteei SM. Study the effect of axially perforated twisted tapes on the thermal performance enhancement factor of a double tube heat exchanger. *Case Studies in Thermal Engineering* 2017;10:161–8.
- [10] Al-Obaidi AR, Alhamid J. The effect of different twisted tape inserts configurations on fluid flow characteristics, pressure drop, thermo-hydraulic performance and heat transfer enhancement in the 3D circular tube. *International Journal of Ambient Energy* 2023;44:57–72. <https://doi.org/10.1080/01430750.2022.2091023>.
- [11] Maxwell JC. A treatise on electricity and magnetism. vol. 1. Clarendon press; 1873.
- [12] Choi SUS, Eastman JA. Enhancing thermal conductivity of fluids with nanoparticles. Argonne National Lab.(ANL), Argonne, IL (United States); 1995.
- [13] Buongiorno J. Convective transport in nanofluids 2006.
- [14] Nguyen CT, Desgranges F, Galanis N, Roy G, Maré T, Boucher S, et al. Viscosity data for Al<sub>2</sub>O<sub>3</sub>–water nanofluid—hysteresis: is heat transfer enhancement using nanofluids reliable? *International Journal of Thermal Sciences* 2008;47:103–11. <https://doi.org/https://doi.org/10.1016/j.ijthermalsci.2007.01.033>.
- [15] Esmaeilzadeh E, Almohammadi H, Nokhosteen A, Motezaker A, Omrani AN. Study on heat transfer and friction factor characteristics of  $\gamma$ -Al<sub>2</sub>O<sub>3</sub>/water through circular tube with twisted tape inserts with different thicknesses. *International Journal of Thermal Sciences* 2014;82:72–83.
- [16] S. Zhang, L. Lu, C. Dong, S.H. Cha, Performance evaluation of a double-pipe heat exchanger fitted with self-rotating twisted tapes, *Appl. Therm. Eng.* 158 (2019), 113770.
- [17] T. Wen, L. Lu, H. Zhong, B. Shen, Thermal properties measurement and performance evaluation of water/ZnO nanofluid in a mini channel with offset fins, *Int. J. Heat Mass Transf.* 162 (2020), 120361.