

A. A. Karamallah

Mechanical Engineering
Department
University of Technology
Baghdad, Iraq
dr_abdulhassank@yahoo.com

N. S. Mahmoud

Mechanical Engineering
Department, University of
Technology Baghdad, Iraq
nabeelsmr@yahoo.com

Numerical Investigation of Heat Transfer Enhancement with CuO Nanofluid Flowing in a Circular Tube Fitted with Twisted Tape Inserts

Abstract- The present paper investigates numerically the enhancement of heat transfer with CuO nanofluid flowing in a horizontal circular tube fitted with different shapes of twisted tape. Finite volume method with ANSYS FLUENT in three dimensions is used in numerical investigation. The effect of twist ratio, concentration of nanofluid, twisted tape type with single phase flow on values of Nusselt number and friction factor are investigated. Heat transfer is enhanced as Reynolds number increases and twist ratio decreases.

Keywords: Heat transfer enhancement; Twisted tape; Nanofluid; Nusselt number

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1. Introduction

Previously, numerous various technical methods have been used in different energy supplying equipment to enhance the less thermal efficiency of traditional heat transfer fluids (water, engine oil, and ethylene glycol), which are highly utilized in many industrial cooling or heating applications. Presently, the performance of the heat exchanger analysis for single phase flows can be enhanced by different technical methods. Generally, the heat transfer can be alienated into two classes; the first is the active heat transfer and the second is the passive heat transfer. Therefore, the computational fluid dynamics modeling technique is utilized as a powerful tool to put on and accepting many industrial processes. In order to explain this extra enhancement, several models were proposed by researchers. Lishan You [1] predicted numerically by finite volume the temperature distribution and velocity for laminar fully developed flow through tube with twisted tape. The heat transfer with uniform temperature of the wall and the boundary conditions of the uniform heat flux at the tube wall were taken into consideration. He introduced the effects of change of temperature and velocity fields with Reynolds no. and tape twist ratio. Also, he described the effect of temperature distribution upon the Prandtl. Both Nusselt no. and the friction factor essentially increase. Eiamsa-ard, et al., [2] studied numerically the clearance ratio of 0.0, 0.1, 0.2 and 0.3 on improving the transfer of

heat, friction and thermal performance with twist ratios of 2.5 and 5.0. The simulation is done for turbulent flow and constant wall temperature with Reynolds number of 3000 to 10,000. It was noted that for 2.5 twist ratio and mentioned values of clearance ratio, the heat transfer rates improves up to 20% to 73.6%, and the friction factor raises from 330% to 160% compared to plane tube. The tube with clearance ratio twisted tape of (0.1, 0.2 and 0.3) gives heat transfer lower than zero clearance ratio by (15.6%, 33.3% and 31.6%). Yangjun, et al. [3] introduced the configuration optimization for a uniformly spaced short-length twisted tape in a circular tube for the turbulent heat transfer in air employing the Computational Fluid Dynamics with angle to be rotated and free space ratio as parameters. It noted that greater transfer of heat and more resistance for flow occur with larger angle. Twist ratio from 2.5 to 8.0 improves the transfer of heat efficiency except at big rotated angle and high Reynolds no. Eiamsa-ard and Seemawute, [4] presented the experimental and numerical results. This is done for flow properties in addition to the local heat transfer coefficient of the decaying flow of turbulent swirl that was induced by the twisted tapes of the short length. The employed twist ratios were (3, 4 and 5) at the section entrance. Uniform heat flux conditions for the flow rates of water within a range of Reynolds number from 5200 to 15,300 were adopted. The results of experiments revealed that the tube with short length shows high local Nusselt no. compared to

that of without swirl generator. Increasing the axial distance, reduces the local Nusselt numbers because of the decaying effect. The twist ratios of 4 and 5 give higher factors of thermal performance. Sami, et al. [5] employed mathematically a model to simulate a swirling flow in a tube. This was generated by a twist tape inserts of an elliptic-cut and conventional one. They studied numerically the influences of the twist ratio of 2.93, 3.91, and 4.89 and cut depths of 0.4, 0.8, and 1.4 cm on the improvement of transfer of heat and friction factor in a laminar flow. The simulation was done using FLUENT-6.3.26. The Reynolds no. ranges from 200 to 2100. The results depicted that elliptic-cut twist tape gives greater heat transfer and friction factor when compared to those with the conventional twist tape. Paul et al. [6] investigated numerically the heat transfer, friction and thermal performance characteristics of CuO/water nanofluid using Ansys Fluent 14.0. The nanofluid was used in a circular tube with a modified alternate axis twisted tape. The concentration of the nanofluid was 0.3 to 0.7% by volume. The twisted ratio was constant at 3. The experiments were done at Reynolds no. of 830 to 1990.

The objective of this simulation is to investigate the turbulent flow convective heat transfer of different types of twisted tape at different twist ratios in a circular tube under constant heat flux boundary condition.

2. Mathematical Model

The mathematical equations used to describe the flow of fluids are the continuity and momentum equations. For flows involving heat transfer, another set of equations is required to describe the energy conservation [7].

- Continuity Equation (Conservation of Mass):

$$\nabla \cdot (\rho \vec{V}) = 0 \tag{1}$$

Momentum Equation:

$$\nabla \cdot (\rho \vec{V} \vec{V}) = -\nabla p + \nabla \cdot (\bar{\tau}) \tag{2}$$

The stress tensor $\bar{\tau}$ is given by:

$$\bar{\tau} = \mu \left[\left(\nabla \vec{V} + \nabla \vec{V}^T \right) - \frac{2}{3} \nabla \cdot \vec{V} I \right] \tag{3}$$

Energy Equation:

$$\nabla \cdot (\vec{V}(\rho E)) = \nabla \cdot (k \nabla T - \rho C_V T') \tag{4}$$

The turbulent model used in the present work was Realizable κ - ϵ (RKE) model [8], which provides superior performance for flows involving rotation, boundary layers under strong adverse pressure gradients, separation, and recirculation,

suitable for complex flows involving severe pressure gradient, separation, and strong streamline curvature [7].

3. Physical Models

The system geometry in the present work consists of a tube, where the working fluid (nanofluid) flows, together with three types of inserts; clockwise and counter clockwise, V shape cut and typical twisted tape twisted tapes.

I. Tube Geometry

The tube test section has a diameter and length ($D_{in} = 0.01715$ m, $Z = 1.5$ m), respectively. In order to make sure the flow is a hydrodynamic fully developed, the length of entrance should be added to the length of test section, figure (1). Regarding the turbulent flow, the length of entrance is (0.5 m) depending on the equation [9]:

$$L_e / D = 4.4 \times (\text{Re})^{\frac{1}{6}} \tag{5}$$

II. Twisted Tape Geometry

It is a finite length strip twisted with different pitches and twist ratios (the pitch is a distance required for the strip to rotate 180°), and as shown in figure (2), the twist ratio is:

$$TR = P / W \tag{6}$$

It is assumed a full contact of twisted tape with the tube surface or the same tube diameter ($W = 0.01715$ m), and thickness and length of the tape are ($Z = 1.5$ m, $t = 0.7$ mm). Three twist ratios (TR = 4, 6, 8) are applied to twisted tape type. The dimensions of the V-cut are taken from [10], who found the optimum cut depth and width as ($e_d = 7.3745$ mm, $e_w = 5.831$ mm), respectively for all twist ratios, as shown in figure (2).

The V-cut is located in each pitch in opposite direction to the previous one. The twisted tape of clockwise-counter clockwise varies its rotation of direction every two pitches distance, as shown in figure (2). All the geometries were drawn using Solidwork software.

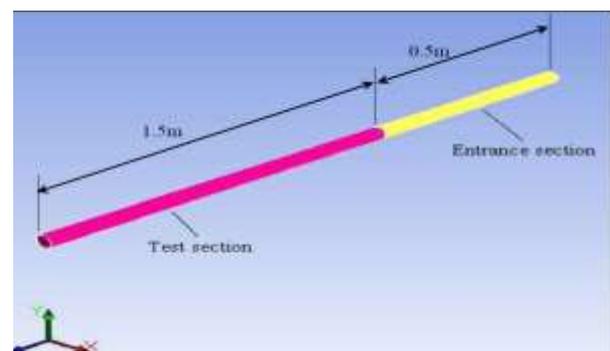


Figure 1: Dimensions of the tube geometry

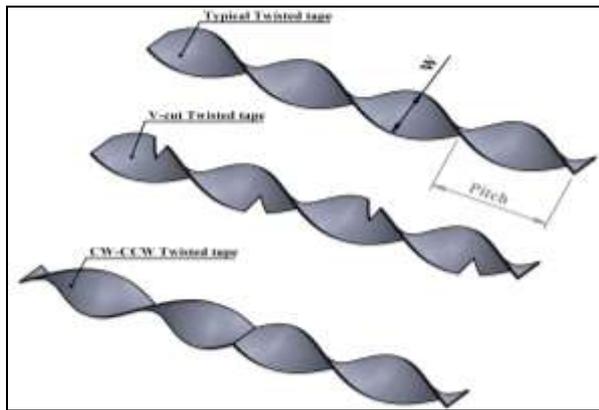


Figure 2: Dimensions of a typical twisted tape

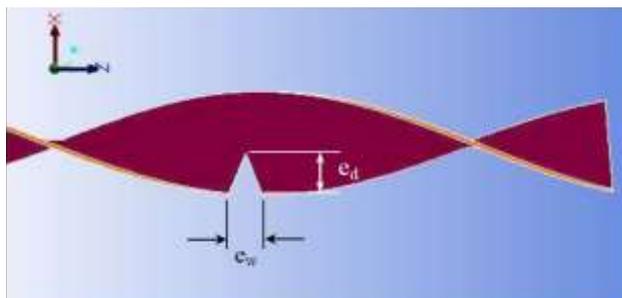


Figure 3: Dimensions of V-cut twisted tape

4. Thermos Physical Properties of Nanofluid

The properties of nanofluid (CuO-water) used in the calculation (density, viscosity and specific heat were provided by Abdulhassan [11] which are experimentally measured at the same concentrations used in the present study ($\phi = 0, 0.01, 0.05, 0.1, 0.5, 1, 2,$ and 3% by volume) as shown:

$$\mu_{nf} = 3 \times 10^{-6} \phi^3 + 1 \times 10^{-5} \phi^2 + 8 \times 10^{-6} \phi + 0.001 \quad (7)$$

$$C_{nf} = -0.0004 \phi^3 + 0.0119 \phi^2 - 0.2337 \phi + 4.183 \quad (8)$$

$$\rho_{nf} = (1 - \phi) \rho_{bf} + \phi \rho_p \quad (9)$$

While, the thermal conductivity was calculated using the formula presented by Vajjha [12]:

$$k_{nf} = [(k_p + 2k_{bf} - 2(k_{bf} - k_p)\phi) / (k_p + 2k_{bf} + (k_{bf} - k_p)\phi)] k_{bf} + 5 \times 10^4 \beta \phi \rho_{bf} C_{bf} \sqrt{(KT) / \rho_p d_p} f(\phi) \quad (10)$$

Where

$$f(\phi) = (2.821 \times 10^{-2} \phi + 3.917) + (-3.0669 \times 10^{-2} \phi - 3.91123 \times 10^{-3})$$

5. Meshing and Numerical Methods

There are mainly two kinds of approaches in volume meshing; the structured mesh, which is excluded in this research as the geometry being considered complex and contains many details,

and the unstructured approach, the grids are in general successful for complex geometries.

For the present work, a unique polyhedral mesh, Figure (4), is used. This mesh allows the simplicity on applying to complex geometry. This can reduce the overall cell count by a factor of 3 to 5 [7]. The above method improves the mesh quality and saves the run time, so convergence is faster. The mesh is created into two steps:

Step I: - Three dimensional tetrahedral meshes are generated using Gambit code.

Step II: - The meshes of polyhedral type are created by an automatic cell agglomeration within FLUENT code.

A fine mesh is used near the surfaces and coarse meshes are at growing distance from the surface.

The mesh was controlled manually which has been achieved through applying boundary layer mesh attached to the tube and twisted tape surfaces as shown in figure (4).

The integral equations are converted to algebraic forms using FVM. The pressure-velocity coupling is solved using SIMPLE algorithm with Second Order Upwind scheme for momentum, turbulence and energy equations for better accuracy. In the calculations, the standard pressure interpolation scheme is used. It is suitable for most kinds of problems.

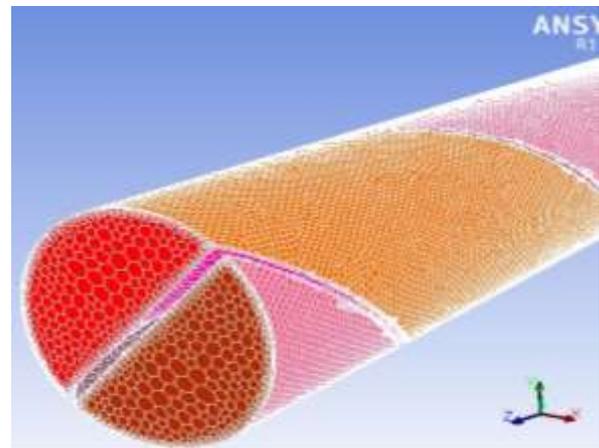


Figure 4: Polyhedral mesh of the fluid domain in a tube with twisted tape

6. Boundary Conditions

In figure (1), the internal domain has been assigned as a fluid. The velocity inlet to the tube is specified over a range of (0.14-1.174 m/sec) depending on the Reynolds number range (2500-20000) of the working fluid. The inlet temperature to the tube is constant at (20°C). No slip boundary condition is identified for the twisted tape and tube surfaces and is set as a wall. A heat flux of (2000-5000 W/m²) is applied to the tube wall.

7. Result Calculations

Local Nusselt number is given by:

$$Nu(z) = h(z)D / k_{nf} \quad (11)$$

The local heat transfer coefficient:

$$h(z) = q / [T_{si}(z) - T_b(z)] \quad (12)$$

The average heat transfer coefficient

$$h_{av} = \frac{1}{L} \int_0^L h(z) dz \quad (13)$$

The average value of Nusselt number is:

$$Nu_{av} = h_{av}D / k_{nf} \quad (14)$$

And, the Reynolds number is

$$Re = (\rho_{nf} \omega D) / \mu_{nf} \quad (15)$$

The following equation is used to calculate the Darcy friction factor:

$$f = [(\Delta p / L)D] / [\rho \omega^2 / 2] \quad (16)$$

8. Results and Discussion

I. Results Validation

To verify the reliability and exactness of the numerical model, the simulated average Nusselt numbers across the tube versus (Re) are compared with those obtained from experiments by [11] as shown in figure (5). An average error of less than 10% is noticed with typical twisted tape (TR = 4).

II. Twist Tape

Figure (6) shows the variations of Nusselt no. with Reynolds no. for the plain tube compared to the twisted tape. As the Reynolds no. increases, the Nusselt no. also increases for all ranges of Reynolds no. and the twisted tape types. Nusselt no. increases with the twist ratio decreasing and the best studied twist ratio is (TR=4). For a tube having a twisted tape, a rotational or secondary flow is generated with the required effects.

Figure (7) shows the variation of friction factor with Reynolds no. for the plain tube compared to the typical twisted tape at three twist ratios (TR = 4, 6, 8), the friction factor decreases as the Reynolds no. and twist ratio increase. As the twist ratio decreases, the secondary flow increases.

The influence of the twisted tape type, The change in Nusselt no. with Reynolds no. for the plain tube compared with the three types of twisted tape for twist ratio (TR=4) is shown in figure (8). The Nusselt no. increases when the twisted tape is converted from typical twisted tape into V-cut twisted tape and to clockwise-counter clockwise twisted tape, for all twist ratios.

The highest improvement in heat transfer ($Nu_{nanofluid}/Nu_{plaintube}$) was (2.41) for the type of

clockwise-counter clockwise twisted tape at a twist ratio of 4 for Reynolds no. (2500).

III. Nanofluid

Figure (9) shows the variation of the average Nusselt number with Reynolds number using clockwise-counter clockwise twisted tape and CuO nanofluid at the concentrations ($\phi = 0.01, 0.05, 0.1, 0.5, 1, 2, 3$ % by volume), the highest Nusselt number. The maximum enhancement in the heat transfer (the Nusselt number ratio) ($Nu_{nanofluid}/Nu_{plaintube}$) for CuO was (7.5) occurred using clockwise-counter clockwise twisted tape at twist ratio (TR = 4), Reynolds no. (2500) and concentration ($\phi=3\%$) as shown in figure (10).

The enhancement in heat transfer coefficient in nanofluid is attributed to the effective thermal conductivity of nanofluid solution. The heat transfer coefficient is given as $(k/\delta t)$, where (δt) is the thickness of thermal boundary layer. That indicates that the improvement of thermal conductivity and/or the nanofluid reduce the thickness of thermal boundary layer increases the coefficient of heat transfer. The thickness of thermal boundary layer for nanofluid is lower than that for the base fluid. Also, the thermal dispersion because of the random motion of particles may be the cause of this improvement. As a result, the temperature gradient at the wall becomes steeper, with an increase in the rate of heat transfer.

IV. Thermal Performance Factor

The thermal performance improvement is required to determine the performance of the heat transfer enhancement. Eiamsa-ard et al. [13] proposed the following expression for constant pumping power calculation:

$$\eta = \frac{\left(\frac{Nu_{enhanced}}{Nu_{plain tube}} \right)}{\left(\frac{f_{enhanced}}{f_{plain tube}} \right)^{\frac{1}{3}}} \quad (17)$$

Generally, the factor of thermal performance above one refers to that the influence of enhancement of heat transfer due to the turbulator (or improvement method) is more effective than the influence of friction increasing.

The maximum thermal performance factor for CuO was (3.7) took place with the type of clockwise-counter clockwise twisted tape at twist ratio =4, Reynolds no. (2500) and concentration ($\phi=3\%$) as shown in figure (11).

8. Conclusions

- 1- In the present work, the used numerical method gives results in good agreement with the experimental results.
- 2- Nusselt number considerably increases with increasing Reynolds number.
- 3- The use of twisted tape increases the heat transfer enhancement, the twist ratio (TR=4) gives higher Nusselt number compared to (TR=6, 8), and the clockwise-counter-clockwise type yields higher Nusselt number compared to the other types of twisted tape. The use of clockwise-counter clockwise tape gives considerably higher Nusselt no. and thermal performance than that of typical twisted tape for all tested Reynolds numbers.
- 4- The combined use of the nanofluid and twisted tape gives a higher heat transfer enhancement compared with the individual utilization of each one and shows that the maximum enhancement in the heat transfer (7.5 times Nusselt number of the distilled water) and thermal performance factor was (3.7) for CuO with the type of clockwise-counter clockwise twisted tape and twist ratio = 4 at Reynolds no. (2500) and concentration ($\phi=3\%$).

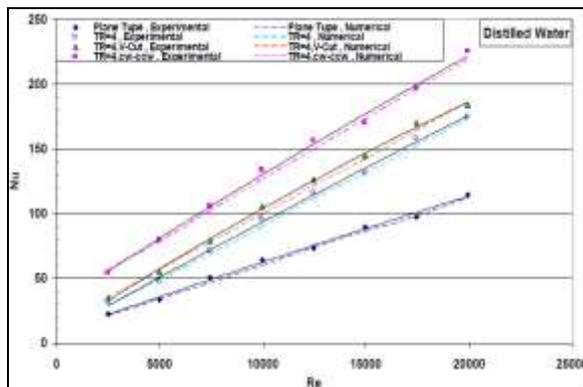


Figure 5: Numerical and experimental results comparison for water.

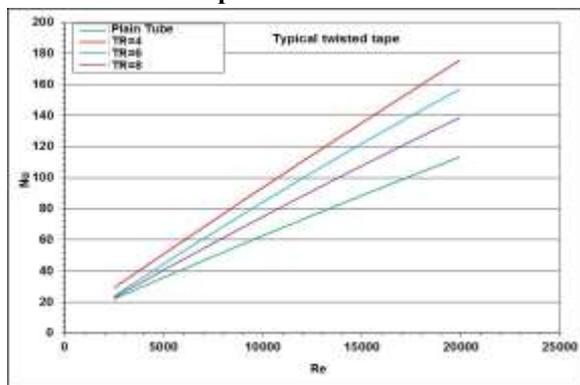


Figure 6: The effect of Re. no. and twist ratio on Nusselt number for water.

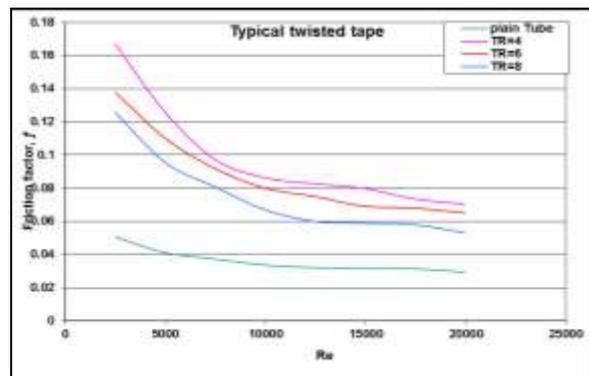


Figure 7: The effect of Re. no. and twist ratios on friction factor for water.

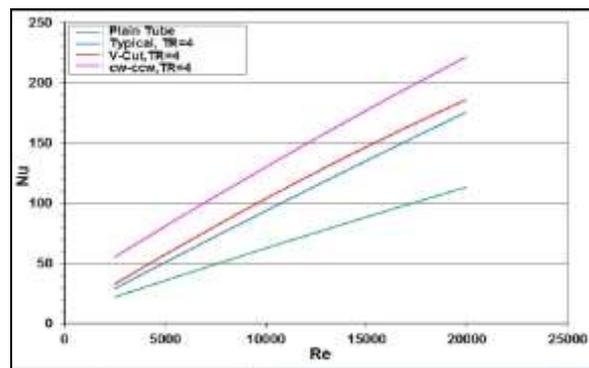


Figure 8: The effect of Re. no. and type of twisted tape for twist ratio =4 on the Nusselt number for water.

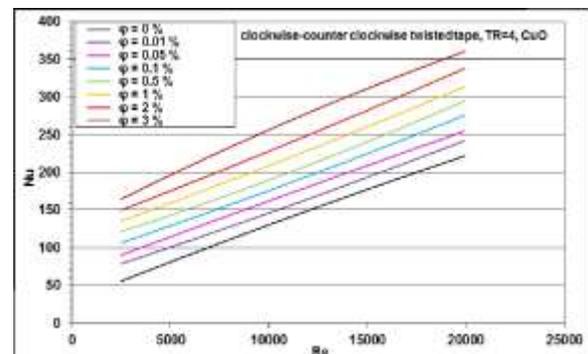


Figure 9: The influence of Reynolds no. on Nusselt number for CuO nanofluid and for different concentrations in a tube with clockwise-counter clockwise twisted tape.

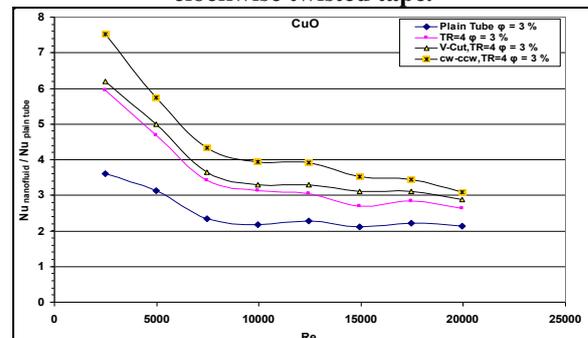


Figure 10: The influence of Reynolds no. and twist tape type on Nusselt number ratio ($Nu_{nanofluid}/Nu_{plain tube}$) for CuO nanofluid and ($\phi = 3\%$).

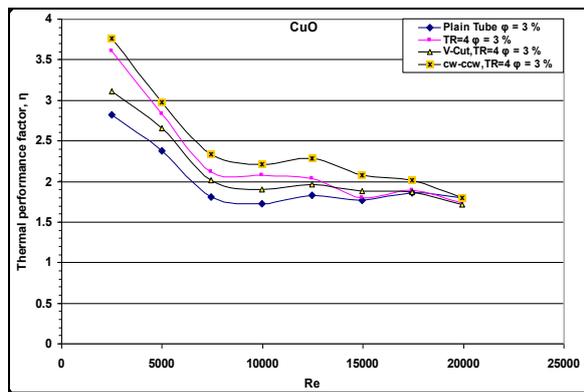


Figure 11: The influence of Reynolds no. and twist tape type on thermal performance factor (η) for CuO nanofluid and concentrations ($\phi = 3\%$)

Nomenclature

- A: Surface area of the tube (m^2)
- C: Specific heat (kJ/kg.K)
- D: Diameter (m)
- d_p : Particle diameter (nm)
- E: Total energy (J)
- e_d : V-cut Depth (m)
- e_w : V-cut width (m)
- h: Heat transfer coefficient ($W/m^2.K$)
- k: Thermal conductivity ($W/m.K$)
- K: Boltzmann's constant (1.38054×10^{-23}) (J/K)
- L: Length (m)
- \dot{m} : Mass flow rate (kg/s)
- Nu: Nusselt number (-)
- p: Pressure (N/m^2)
- P: pitch distance (m)
- Pr: Prandtl number (-)
- q: Heat flux (W/m^2)
- Re: Reynolds number (-)
- T: Temperature ($^{\circ}C$)
- TR: Twist ratio (-)
- u, v, w: Velocity component in Cartesian coordinate (m/s)
- V: Velocity vector (m/s)
- W: Tape width (m)
- Z: Test section length (m)
- β : Thermal expansion coefficient (1/K)
- μ : Dynamic viscosity (kg/m.s)
- ν : Kinematic viscosity (m^2/s)
- ϵ : Dissipation rate (1/s)
- η : Thermal performance factor (-)
- κ : Turbulent kinetic energy (m^2/s^2)
- ρ : Density (kg/m^3)
- τ : Viscous stress tensor (N/m^2)

Subscripts

- b: Bulk
- bf: Base fluid
- e: Entrance
- f: Fluid
- nf: Nanofluid
- P: Partical
- s: Surface

si: Inner surface

Superscript

(\prime): Fluctuation component

T: Transpose

Abbreviation

CFD: Computational fluid dynamic

cw-ccw: Clockwise-counter clockwise twisted tape

TT: Typical twisted tape

V-cut: Twisted tape with V-cut

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Author's biography



Prof. Dr. Abdulhassan A. Karamallah, Mechanical Eng. Dept., University of Technology / Baghdad-Iraq.

He published more than 82 articles in aerodynamics, combustion, heat transfer and application of nanofluids.

Membership of many international and local conferences. Peer reviewer of many international journal and conferences.

Prof. Karamallah is now the chairman of the postgraduate studies for the University of Technology -Iraq.



Dr. Nabeel Sameer Mahmoud, was born in Iraq 1975, BSc. 1997, Mechanical Engineering from Al-Nahrain University, M.Sc. 2000 in Refrigeration & Air conditioning and Ph.D. 2014 in Thermal Power from the University of Technology / Baghdad-Iraq.

Member of Iraqi Engineers Association. He is currently a lecturer at the University of Technology/ Mechanical Eng. Dept., University of Technology/ Baghdad-Iraq. His research interests are Heat Transfer, Fluid flow, CFD simulation and Refrigeration & Air conditioning.