A REVIEW OF COMPUTATIONAL FLUID DYNAMICS ANALYSIS FOR HEAT TRANSFER ENHANCEMENT IN SHELL AND TUBE HEAT EXCHANGERS

Pankaj Kumar Bangre[1], Vineet Kumar Dwivedi[2]

[1]Scholar, School of Mechanical Engineering, Faculty of Engineering and Technology, SAM Global University, Bhopal, M.P, 462022, India.

[2]Head and Prof., School of Mechanical Engineering, Faculty of Engineering and Technology, SAM Global University, Bhopal, M.P, 462022, India.

ABSTRACT

Computational Fluid Dynamics (CFD) has revolutionized the analysis and optimization of heat exchangers by providing a detailed understanding of fluid flow behavior, heat transfer mechanisms, and turbulence effects. This paper explores the application of CFD in the study of shell and tube heat exchangers, specifically focusing on the enhancement of heat transfer using graphene oxide nanofluid. The Navier-Stokes equations govern fluid motion and momentum transfer, essential for predicting pressure distributions and velocity profiles within the exchanger. The energy equation accounts for thermal energy conservation, incorporating terms for conduction, convection, and thermal radiation, crucial for evaluating temperature distributions and thermal efficiency. Additionally, turbulence models such as the k-epsilon model capture turbulent flow characteristics, aiding in the accurate prediction of heat transfer rates and fluid mixing. Through comprehensive CFD simulations, this study aims to optimize the design of a shell and tube heat exchanger with a helical coil using graphene oxide nanofluid, exploring its potential to enhance heat transfer efficiency. The findings underscore the significance of CFD in advancing heat exchanger technology, offering insights into improving thermal performance and operational reliability across various industrial applications.

Keywords: Computational Fluid Dynamics (CFD), Heat Exchanger, Shell and Tube, Graphene Oxide Nanofluid, Heat Transfer Enhancement, Turbulence Modeling

1. INTRODUCTION

Heat exchangers play a crucial role in various industries, including power generation, chemical processing, and HVAC systems, by facilitating efficient heat transfer between fluids. Among the various types, shell and tube heat exchangers are widely used due to their robust design and versatility. To enhance their thermal performance, researchers have explored innovative modifications such as incorporating helical coils. Helical coils introduce secondary flows, increasing turbulence and improving heat transfer rates. In recent years, nanofluids—fluids containing nanoparticles—have gained significant attention for their superior thermal properties. Graphene oxide nanofluid, in particular, exhibits excellent thermal conductivity, stability, and heat transfer capabilities, making it a promising candidate for enhancing heat exchanger performance. Computational Fluid Dynamics (CFD) is a powerful tool used to simulate and analyze the complex thermal and fluid flow behaviors within heat exchangers. This review paper aims to provide a comprehensive overview of the CFD investigations into heat transfer enhancement in shell and tube heat exchangers with helical coils using graphene oxide nanofluid. By examining recent studies, this paper will highlight the potential benefits and challenges associated with these advanced materials and designs, offering insights into future research directions and practical applications for improved thermal management in various industrial processes.

Effective heat removal and management are crucial for high-power, compact technologies. Nanofluids have attracted significant global scientific interest as a solution to these challenges. They can be custom-designed to meet specific requirements, making them a flexible cooling method adaptable to different systems. Essentially, nanofluids have the potential to become the world's first smart/adaptable coolants [1,2]. The term "nanofluids," coined by Choi and Eastman [3], refers to multiphase systems comprising a base fluid and a stable suspension of nanometer-sized particles. These nanofluids can be produced through either a one-step process, creating the host fluid and nanoparticles together, or a two-step process, where they are created separately and then mixed [4]. Nanofluids have been extensively studied due to their unique and often anomalous thermal transport properties. Their study has yielded valuable scientific knowledge and revealed nearly limitless industrial and commercial applications [5,6]. Recent research has extended into cryogenic nanofluids, which combine extreme cryogenic temperatures with the adaptable thermal transport characteristics of traditional nanofluids, showing promise for next-generation cryogenic fluids with enhanced thermophysical properties [4,7]. The diversity of nanofluids is vast, with new ones created by mixing different base fluids or nanoparticles. Even minor methodological changes can significantly impact the final product [8]. Effective heat transfer applications, crucial for daily life, require ongoing research to improve efficiency [10].

Advances in manufacturing have led to products with small sizes, high heat flux, and non-uniform heat flux, increasing the demand for efficient heat rejection solutions [11]. Forced convection using liquid coolants in laminar or turbulent flow regimes remains a key solution, though it often results in higher pressure loss and increased pumping power [12,13]. Common heat transfer liquids like water, ammonia, ethylene glycol, and mineral oil have low thermal conductivity and high viscosity, leading to inefficient convective performance and complex compact heat rejection device design. Innovative coolants like nanofluids, offering improved heat transfer properties, are therefore needed [15,16]. Efforts to enhance the fluid heat transfer coefficient have focused on the properties of heat transfer fluids, surface characteristics (extension, shape, and roughness), and fluid motion (laminar or turbulent). Recent studies have explored using carbon-based nanostructures, particularly graphene, a single-atom-thick sheet of hexagonally arrayed sp2-bonded carbon atoms, known for its unique electrical properties and high carrier mobility [17]. Graphene's densely organized atomic-scale honeycomb pattern serves as a fundamental structure for other sp2 carbon-bonded nanostructure materials, such as carbon nanotubes [22] and fullerene [23].

2. HEAT EXCHANGER CLASSIFICATION

Heat exchangers can be classified based on various criteria such as their construction, flow arrangement, and heat transfer mechanisms. Here is a brief overview of the main classifications:

1.1. Classification by Construction

i. Shell and Tube Heat Exchangers: Consist of a series of tubes, one set carrying the hot fluid and the other set carrying the cold fluid. The tubes are enclosed in a cylindrical shell.

ii. Plate Heat Exchangers: Comprise multiple thin, corrugated plates stacked together, with hot and cold fluids flowing through alternate channels.

iii. AirCooled Heat Exchangers: Use air to cool the fluid, often involving fans or natural convection.

Double Pipe Heat Exchangers: Feature two concentric pipes, with one fluid flowing through the inner pipe and the other fluid flowing through the annular space between the pipes.

1.2. Classification by Flow Arrangement

i. Counterflow Heat Exchangers: Fluids flow in opposite directions, which maximizes the temperature difference and heat transfer efficiency.

ii. Parallel Flow Heat Exchangers: Fluids flow in the same direction, leading to lower temperature differences and heat transfer rates.

iii. Crossflow Heat Exchangers: Fluids flow perpendicular to each other, commonly used in applications like radiators and air conditioning units.

1.3. Classification by Heat Transfer Mechanism

i. Direct Contact Heat Exchangers: Fluids come into direct contact, mixing and transferring heat directly, such as in cooling towers.

ii. Indirect Contact Heat Exchangers: Fluids are separated by a solid barrier (such as a tube or plate), with heat transfer occurring through the barrier without direct fluid contact.

1.4. Classification by Number of Passes

i. Single Pass Heat Exchangers: Fluids pass through the exchanger once.

ii. Multi Pass Heat Exchangers: Fluids pass through the exchanger multiple times, increasing heat transfer efficiency.

1.5. Classification by Application

i. Condensers: Used to condense vapor into liquid by removing heat.

ii. Evaporators: Used to convert liquid into vapor by adding heat.

iii. Regenerative Heat Exchangers: Use the same fluid to heat and cool, often found in systems requiring heat recovery.

SHELL AND TUBE HEAT EXCHANGER STRUCTURES AND GEOMETRY

Shell and tube heat exchangers are among the most common types of heat exchangers due to their robust design and versatility. They consist of the following key components:

2.1. Shell

Description: A large cylindrical vessel that encases the tube bundle.

Material: Typically made of metal, such as stainless steel or carbon steel, to withstand high pressures and temperatures.

Function: Contains one of the fluids (usually the cooling fluid) and directs it over the tube bundle for heat exchange.

2.2. Tube Bundle

Description: A collection of tubes through which the second fluid flows.

Types of Tubes:

Straight Tubes: Simple, straight tubes fixed at both ends.

U Tubes: Bent into a U shape, allowing for thermal expansion and contraction.

Material: Often made of metals like copper, stainless steel, or titanium, depending on the application and fluid properties.

Function: Carries the second fluid (usually the heated fluid) and facilitates heat exchange with the shell side fluid.

2.3. Tube Sheets

Description: Plates at both ends of the shell that hold the tubes in place.

Material: Made of metal, similar to the tubes and shell, to ensure compatibility and durability.

Function: Provide structural support and seal the ends of the tubes to prevent fluid leakage.

2.4. Baffles

Description: Metal plates placed within the shell.

Types:

Segmental Baffles: Most common, with a semicircular cut to direct flow across the tubes.

Disc and Doughnut Baffles: Alternating discs and rings to create a zigzag flow path.

Helical Baffles: Spiral shaped baffles for smoother fluid flow and reduced pressure drop.

Function: Enhance heat transfer by directing the shell side fluid flow across the tube's multiple times, increasing turbulence and improving thermal contact.

2.5. End Covers (Heads)

Description: Covers attached to the ends of the shell, housing the tube sheets.

Types:

Fixed Tube Sheet Design: Tube sheets are permanently fixed to the shell.

Floating Head Design: One end of the tube bundle can move, accommodating thermal expansion.

U Tube Design: Tubes are bent into a U shape, with only one tube sheet.

Function: Seal the ends of the shell and provide access to the tube bundle for maintenance and cleaning.

2.6. Nozzles

Description: Inlet and outlet connections for the fluids.

Placement: Typically located on the shell and end covers.

Function: Facilitate the entry and exit of the fluids into the shell and tube sides.

2.7. Supports

Description: Structures that hold the heat exchanger in place.

Types:

Saddle Supports: Used for horizontal exchangers.

Brackets: Used for vertical exchangers.

Function: Provide stability and support to the heat exchanger during operation.

Geometry Considerations

Tube Diameter and Length: Selected based on the required heat transfer surface area and fluid flow rates.

Tube Pitch: The distance between the centers of adjacent tubes, affecting the flow dynamics and heat transfer efficiency.

Baffle Spacing: The distance between adjacent baffles, influencing the flow pattern and turbulence of the shell side fluid.

Shell Diameter: Determined by the number of tubes and the required flow area for the shell side fluid.

Number of Passes: The number of times the tube side fluid flows back and forth through the tube bundle, affecting the heat transfer rate and pressure drop.
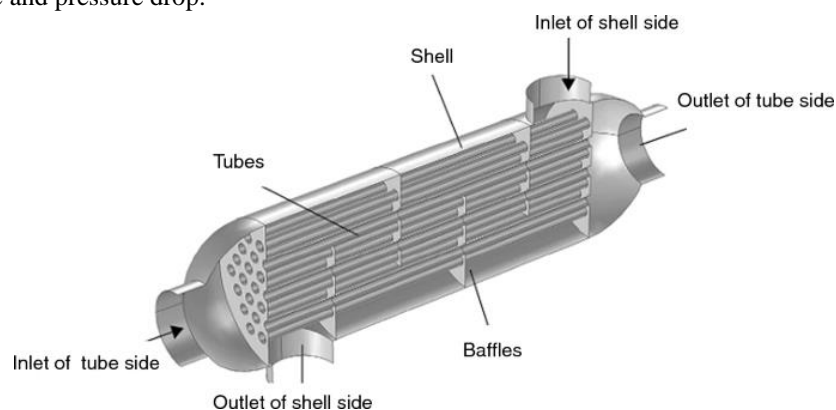
Figure 1: Structure of Shell and Tube Heat Exchanger [24]

3. EQUATIONS USED

ANSYS Fluent is a widely used computational fluid dynamics (CFD) software that allows engineers and researchers to simulate and analyze fluid flow, heat transfer, and other related phenomena. When conducting a thermal analysis using ANSYS Fluent, several models, equations, and assumptions can be employed. Below, I'll outline some of the key aspects typically considered in a thermal analysis using ANSYS Fluent for a review paper.

3.1 Continuity Equation

The continuity equation represents mass conservation and is given by:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0$$

Where,

ρ = density of the fluid

u = fluid velocity vector

∇ = del operator

3.2 Navier Stoke's Equation

The Navier-Stokes equations govern fluid motion and are given by:

$$\frac{\partial \rho u}{\partial t} + \nabla \cdot (\rho u u) = -\nabla P + \nabla \cdot \tau + \rho g$$

Where,

P is the pressure

τ is the stress tensor

g is the body force vector (e.g., gravitational force).

Energy Equation

The energy equation accounts for heat transfer and is given by:

$$\partial(\rho E)/\partial t + \nabla \cdot (\rho u E + q) = \nabla \cdot (k\nabla T) + Q$$

ρ represents the fluid density.

E is the total energy per unit mass, which includes internal energy, kinetic energy, and potential energy.

t is time.

u is the fluid velocity vector.

q is the heat flux vector, which represents the convective heat transfer.

k is the thermal conductivity of the fluid.

T is the temperature.

Q is the volumetric heat source/sink term.

Turbulence Model

In many cases, the flow might be turbulent. Several turbulence models can be used, such as:

Reynolds-Averaged Navier-Stokes (RANS) models: k-ε, k-ω SST, etc.

Large Eddy Simulation (LES).

Reynolds Stress Model (RSM).

Boundary Conditions

Appropriate boundary conditions must be set to define the flow and thermal behavior at the domain boundaries. Examples include:

Inlet velocity and temperature profiles.

Outlet pressure or mass flow rate boundary.

Wall boundary conditions (no-slip, wall temperature, heat flux, etc.).

Material Properties

Fluid properties like density ρ, Thermal Conductivity k, Specific Heat Capacity Cp, Dynamic Viscosity μ, Thermal Expansion Coefficient β, Prandtl Number Pr, Thermal Diffusivity α, Thermal Expansion Coefficient β.

4. CONCLUSION

In conclusion, Computational Fluid Dynamics (CFD) plays a pivotal role in the analysis of heat exchangers, offering detailed insights into fluid flow dynamics, heat transfer mechanisms, and turbulence characteristics. The Navier-Stokes equations form the foundation for modeling fluid motion and pressure distribution within the exchanger, crucial for optimizing design and performance. The energy equation accounts for energy conservation, incorporating terms for heat conduction, viscous dissipation, and heat generation, essential for predicting temperature profiles and thermal efficiency.

Additionally, turbulence models like the k-epsilon model provide further refinement by simulating turbulent flow behavior, aiding in accurate predictions of heat transfer rates and pressure drops.

Overall, CFD enables engineers to simulate and analyze complex heat exchanger systems with precision, facilitating the development of efficient designs that meet performance requirements across various industrial applications. As advancements in simulation capabilities continue, the integration of CFD remains integral to advancing heat exchanger technology towards enhanced efficiency and reliability in thermal management.

5. REFERENCES

[1] Sharifpur M, Adio SA, Meyer JP. Experimental investigation and model development for effective viscosity of Al2O3–glycerol nanofluids by using dimensional analysis and GMDH-NN methods. Int Commun Heat Mass Transfer 2015;68:208–19.

[2] Sharma AK, Tiwari AK, Dixit AR. Rheological behaviour of nanofluids: a review. Renew Sustain Energy Rev 2016;53:779–91.

[3] Choi SUS, Eastman J. Enhancing thermal conductivity of fluids with nanoparticles. IL (United States): Argonne National Lab.; 1995. p. 99–105.

[4] Mehrali M, Sadeghinezhad E, Latibari S Tahan, Kazi SN, Mehrali M, Zubir MNBM, et al. Investigation of thermal conductivity and rheological properties of nanofluids containing graphene nanoplatelets. Nanoscale Res Lett 2019;9:1–12.

[5] Graphene: synthesis, properties, and phenomena. Wiley-VCH Verlag GmbH & Co. KGaA; 2020.

[6] Park SD, Won Lee S, Kang S, Bang IC, Kim JH, Shin HS, et al. Effects of nanofluids containing graphene/graphene-oxide nanosheets on critical heat flux. Appl Phys Lett 2010;97:023103.

[7] Mehrali M, Sadeghinezhad E, Latibari S Tahan, Mehrali M, Togun H, Zubir MNM, et al. Preparation, characterization, viscosity, and thermal conductivity of nitrogen-doped graphene aqueous nanofluids. J Mater Sci 2019;49:7156–71.

[8] Poh HL, Sanek F, Ambrosi A, Zhao G, Sofer Z, Pumera M. Graphenes prepared by Staudenmaier, Hofmann and Hummers methods with consequent thermal exfoliation exhibit very different electrochemical properties. Nanoscale 2020;4:3515–22.

[9] Park JS, Kihm KD, Kim H, Lim G, Cheon S, Lee JS. Wetting and evaporative aggregation of nanofluid droplets on CVD-synthesized hydrophobic graphene surfaces. Langmuir 2019;30:8268–75.

[10] Li H, Jiang M, Li Q, Li D, Chen Z, Hu W, et al. Aqueous preparation of polyethylene glycol/sulfonated graphene phase change composite with enhanced thermal performance. Energy Convers Manage 2021;75:482–7.

[11] Tao YB, Lin CH, He YL. Preparation and thermal properties characterization of carbonate salt/carbon nanomaterial composite phase change material. Energy Convers Manage 2019;97:103–10.

[12] Mehrali M, Sadeghinezhad E, Rosen MA, Akhiani AR, Latibari S Tahan, Mehrali M, et al. Heat transfer and entropy generation for laminar forced convection flow of graphene nanoplatelets nanofluids in a horizontal tube. Int Commun Heat Mass Transfer 2019;66:23–31.

[13] Mehrali M, Sadeghinezhad E, Rosen MA, Latibari S Tahan, Mehrali M, Metselaar HSC, et al. Effect of specific surface area on convective heat transfer of graphene nanoplatelet aqueous nanofluids. Exp Thermal Fluid Sci 2015;68:100–8.

[14] Saidur R, Leong KY, Mohammad HA. A review on applications and challenges of nanofluids. Renew Sustain Energy Rev 2011;15:1646–68.

[15] Sadeghinezhad E, Mehrali M, Latibari S Tahan, Mehrali M, Kazi SN, Oon S, et al. Experimental investigation of convective heat transfer using graphene nanoplatelet based nanofluids under turbulent flow conditions. Ind Eng Chem Res 2014;53:12455–65.

[16] Liu J, Ye Z, Zhang L, Fang X, Zhang Z. A combined numerical and experimental study on graphene/ionic liquid nanofluid based direct absorption solar collector. Sol Energy Mater Sol Cells 2019;136:177–86.

[17] Moghaddam MB, Goharshadi EK, Entezari MH, Nancarrow P. Preparation, characterization, and rheological properties of graphene–glycerol nanofluids. Chem Eng J 2020;231:365–72.

[18] Mehrali M, Latibari ST, Mehrali M, Indra Mahlia TM, Metselaar HS Cornelis. Preparation and properties of highly conductive palmitic acid/graphene oxide composites as thermal energy storage materials. Energy 2013;58:628–34.

[19] Mehrali M, Latibari ST, Mehrali M, Mahlia TMI, Metselaar HSC, Naghavi MS, et al. Preparation and characterization of palmitic acid/graphene nanoplatelets composite with remarkable thermal conductivity as a novel shape-stabilized phase change material. Appl Therm Eng 2013;61:633–40.

[20] Novoselov K, Geim AK, Morozov S, Jiang D, Zhang Y, Dubonos S, et al. Electric field effect in atomically thin carbon films. Science 2004;306:666–9.

[21] Eatemadi A, Daraee H, Karimkhanloo H, Kouhi M, Zarghami N, Akbarzadeh A, et al. Carbon nanotubes: properties, synthesis, purification, and medical applications. Nanoscale Res Lett 2014;9:1–13. E. Sadeghinezhad et al. / Energy Conversion and Management 111 (2016) 466–487 485

[22] Kroto H, Heath J. C60: buckminsterfullerene. Nature 1985;3:162–3.

[23] Iijima S. Helical microtubules of graphitic carbon. Nature 1991;354:56–8.

[24] Marzouk, S.A., Abou Al-Sood, M.M., El-Said, E.M.S. *et al.* A comprehensive review of methods of heat transfer enhancement in shell and tube heat exchangers. *J Therm Anal Calorim* **148**, 7539–7578 (2023). https://doi.org/10.1007/s10973-023-12265-3