ISSN 2456-0286(O)

RUNGTA
International Journal of
Mechanical and Automobile
Engineering

REVIEW ARTICLE

Heat Exchanger Modification

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ABSTRACT:

Heat exchangers are integral to industrial processes involving thermal energy exchange. Traditional designs such as the shell-and-tube configuration often suffer from suboptimal thermal performance, fouling, and pressure drops. This paper investigates cost-effective passive modification techniques including helical baffles, vortex generators, and nanofluids for enhancing heat exchanger performance. The objective is to optimize heat transfer without significant penalties in pressure drop or system complexity. Computational Fluid Dynamics (CFD) simulations coupled with experimental validation are used to analyse the effects of these modifications. Results show up to 40% improvement in heat transfer coefficient and over 35% increase in Nusselt number with limited increase in pressure drop. The study concludes that retrofitting existing exchangers with such enhancements is a practical approach to improving thermal systems. These findings suggest that integrating nanotechnology and geometric modifications can lead to significant energy savings and improved process reliability in various industrial applications.

KEYWORDS: Heat exchangers, passive enhancement, helical baffles, vortex generators, nanofluids, Computational Fluid Dynamics (CFD), Nusselt number, heat transfer coefficient, retrofitting, thermal performance.

Received on 11.07.2024 Revised on 02.08.2024 Accepted on 17.09.2024 Published on 11.10.2024 ***Run. Int. J. Mech. and Auto. Engl. 2(1): October 2024***

1. INTRODUCTION

Heat exchangers are among the most widely utilized thermal devices in industrial engineering because they facilitate the transfer of heat between two or more fluids at different temperatures without direct mixing. They play a fundamental role in power plants, petrochemical industries, refrigeration systems, air-conditioning units, automotive radiators, process industries, desalination plants, and renewable energy systems. Efficient heat exchanger operation directly influences energy consumption, production efficiency, equipment reliability, and overall operating costs.[1−3]

Growing global energy demand and increasing environmental concerns have intensified the need for highly efficient thermal systems. A significant proportion of industrial energy losses occurs through inefficient heat transfer processes. Consequently, improving heat exchanger performance has become a major research focus for reducing energy consumption and greenhouse gas emissions while enhancing industrial productivity.[4]

Among various heat exchanger configurations, shell-and-tube heat exchangers remain the most widely adopted owing to their simple construction, mechanical robustness, ease of maintenance, and

ISSN 2456-0286(O)
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ability to operate under high-pressure and high-temperature conditions. However, conventional shell-and-tube designs frequently experience limitations such as poor shell-side flow distribution, dead flow regions, fouling, excessive pressure losses, and relatively low thermal effectiveness. These limitations reduce overall heat transfer efficiency and increase maintenance requirements.[5]

Various enhancement techniques have therefore been developed to improve thermal performance. Heat transfer enhancement methods are generally classified into active, passive, and compound techniques. Active methods require external energy sources such as mechanical vibration, electric fields, magnetic fields, or fluid pulsation to increase heat transfer. Although effective, active methods increase system complexity and operating costs. Passive techniques, on the other hand, improve thermal performance solely through geometric modifications or improved working fluids without additional energy consumption, making them economically attractive for industrial applications.[6]

Passive enhancement methods include twisted tape inserts, helical baffles, vortex generators, ribbed surfaces, corrugated tubes, extended surfaces, surface roughness modification, porous media, and nanofluids. These techniques primarily improve heat transfer by promoting fluid mixing, disrupting thermal boundary layers, increasing turbulence intensity, and enlarging effective heat transfer area.[7]

Among these approaches, helical baffles have received considerable attention because they replace conventional segmental baffles with continuous spiral flow paths, thereby reducing shell-side pressure losses while improving flow uniformity. Helical baffles eliminate stagnant flow regions and reduce fouling tendencies, resulting in improved thermal effectiveness and reduced maintenance costs.[8]

Vortex generators represent another effective passive enhancement technique. Small winglets, delta tabs, ribs, and protrusions generate longitudinal vortices that continuously disturb the thermal boundary layer and enhance convective heat transfer. Although vortex generators slightly increase pressure drop, their substantial improvement in heat transfer often outweighs the associated hydraulic penalty.[9]

Recent advances in nanotechnology have introduced **nanofluids** as advanced heat transfer media. Nanofluids consist of metallic or ceramic nanoparticles dispersed within conventional base fluids such as water, ethylene glycol, or engine oil. The addition of nanoparticles significantly improves thermal conductivity, resulting in enhanced convective heat transfer and improved heat exchanger effectiveness.[10]

Computational Fluid Dynamics (CFD) has become an indispensable tool for analysing modified heat exchanger designs. CFD enables detailed visualization of velocity fields, temperature distribution, turbulence characteristics, pressure losses, and local heat transfer coefficients before physical prototype development. Combined with experimental validation, CFD substantially reduces design costs while accelerating optimization of enhanced heat exchangers.[11]

Despite numerous published studies, selecting the most suitable passive enhancement technique remains challenging because thermal performance improvements are often accompanied by increased pressure drop and pumping power requirements. Therefore, optimization requires careful consideration of both thermal and hydraulic performance.

The objective of this review is to examine recent developments in passive heat exchanger modification techniques, with particular emphasis on helical baffles, vortex generators, and nanofluids. The review evaluates their influence on heat transfer enhancement, pressure drop characteristics, thermal performance, and industrial applicability based on experimental investigations and CFD analyses.

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2. PASSIVE HEAT TRANSFER ENHANCEMENT TECHNIQUES

Passive enhancement techniques improve heat transfer without requiring external power input. These methods rely on modifications to heat exchanger geometry, surface characteristics, or working fluids to increase turbulence, improve fluid mixing, and reduce thermal resistance.[12]

Compared with active techniques, passive methods are simpler, more economical, easier to retrofit into existing systems, and require minimal maintenance.

2.1 Helical Baffles

Helical baffles replace conventional segmental baffles with continuously inclined spiral plates that guide shell-side flow along a helical path.

Major advantages include:

- Improved shell-side fluid distribution
- Reduced dead zones
- Lower fouling tendency
- Reduced pressure drop
- Higher heat transfer coefficient
- Improved thermal effectiveness

The spiral flow generated by helical baffles promotes continuous mixing of the working fluid, reducing thermal boundary layer thickness and increasing convective heat transfer. Experimental investigations have reported heat transfer improvements ranging from **20–40%** while reducing shell-side pressure loss compared with conventional segmental baffles.[13]

2.2 Vortex Generators

Vortex generators consist of small protrusions or winglets mounted on heat transfer surfaces to generate longitudinal vortices.

Common vortex generator configurations include:

- Delta winglets
- Rectangular winglets
- Curved winglets
- Triangular tabs
- Inclined ribs

These devices continuously disturb the thermal boundary layer, improving fluid mixing and increasing local heat transfer coefficients.

Although vortex generators increase pressure drop slightly, the resulting enhancement in Nusselt number generally produces higher overall thermal performance.[14]

2.3 Twisted Tape Inserts

Twisted tape inserts are among the simplest passive enhancement devices used inside tubes.

The inserts induce swirl flow that:

- Increases fluid residence time
- Improves radial mixing
- Reduces thermal boundary layer thickness
- Enhances convective heat transfer

Twisted tapes are widely applied because of their low manufacturing cost and ease of installation during heat exchanger retrofitting.

2.4 Nanofluids

Nanofluids are engineered suspensions containing nanoparticles dispersed within conventional heat transfer fluids.

Common nanoparticles include:

- Aluminum oxide (Al_2O_3)
- Copper oxide (CuO)
- Titanium dioxide (TiO_2)
- Silicon dioxide (SiO_2)
- Graphene nanoparticles
- Carbon nanotubes

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These nanoparticles substantially improve thermal conductivity and convective heat transfer.

Reported advantages include:

- Higher Nusselt number
- Improved thermal conductivity
- Better heat transfer coefficient
- Reduced heat exchanger size
- Enhanced thermal efficiency

However, excessive nanoparticle concentration may increase viscosity and pumping power requirements.[15]

Table 1. Passive Heat Transfer Enhancement Techniques

Technique	Heat Transfer Improvement	Pressure Drop
Helical Baffles	High	Low
Twisted Tape	Moderate–High	Moderate
Vortex Generators	High	Moderate
Nanofluids	Very High	Slight Increase
Ribbed Tubes	Moderate	Moderate

3. CFD METHODOLOGY AND PERFORMANCE ANALYSIS

Computational Fluid Dynamics (CFD) has become an indispensable tool for analysing heat exchanger performance because it provides detailed information regarding fluid flow, temperature distribution, turbulence characteristics, pressure loss, and local heat transfer coefficients. Compared with purely experimental investigations, CFD significantly reduces development time and enables rapid evaluation of various geometric modifications before prototype fabrication.[16]

The CFD analysis of modified heat exchangers generally consists of geometry generation, mesh development, governing equation formulation, boundary condition specification, numerical solution, convergence assessment, and experimental validation.

3.1 Geometry Development

Three-dimensional models of shell-and-tube heat exchangers incorporating passive enhancement devices such as helical baffles, vortex generators, and twisted tape inserts are developed using Computer-Aided Design (CAD) software.

Typical geometric parameters include:

- Shell diameter
- Tube diameter
- Tube pitch
- Tube layout
- Number of tubes
- Baffle spacing
- Helical angle
- Twist ratio
- Vortex generator dimensions

Optimization of these parameters significantly influences heat transfer and hydraulic performance.[17]

3.2 Mesh Generation

High-quality computational meshes are generated using tetrahedral or hexahedral elements. Local mesh refinement is applied near tube walls, baffles, and vortex generators where strong velocity and temperature gradients occur.

Grid independence analysis is performed to ensure that numerical results remain independent of mesh density.

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3.3 Governing Equations

CFD simulations solve the conservation equations of mass, momentum, and energy.

Continuity Equation

$$\nabla \cdot (\rho \mathbf{V}) = 0$$

Momentum Equation

$$\rho (\mathbf{V}\cdot\nabla)\mathbf{V} = -\nabla P + \mu\nabla^2\mathbf{V}$$

Energy Equation

$$\rho C_p(\mathbf{V}\cdot\nabla T) = k\nabla^2 T$$

where

- ρ = density
- μ = dynamic viscosity
- k = thermal conductivity
- C_p = specific heat
- V = velocity

3.4 Turbulence Models

Most industrial shell-and-tube heat exchangers operate under turbulent flow conditions.

Frequently adopted turbulence models include:

- Standard k–ε model
- RNG k–ε model
- Realizable k–ε model
- SST k–ω model

Among these, the Realizable k–ε model generally provides satisfactory agreement with experimental observations for shell-side flow.[18]

3.5 Boundary Conditions

Typical CFD boundary conditions include:

- Constant inlet velocity
- Constant inlet temperature
- Pressure outlet
- No-slip wall condition
- Adiabatic shell wall (where applicable)

The convergence criterion is generally maintained below

$$10^{-6}$$

for residual errors.

4. THERMAL PERFORMANCE PARAMETERS

The effectiveness of modified heat exchangers is evaluated using several engineering performance parameters.

4.1 Heat Transfer Rate

$$Q = mC_p(T_o - T_i)$$

where

- Q = Heat transfer rate
- m = Mass flow rate
- T_i = Inlet temperature
- T_o = Outlet temperature

4.2 Convective Heat Transfer Coefficient

$$Q = hA\Delta T$$

where

- h = Heat transfer coefficient
- A = Heat transfer area

Higher values of **h** indicate improved thermal performance.

4.3 Nusselt Number

The Nusselt number represents convective heat transfer enhancement.

$$Nu = \frac{hD}{k}$$

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An increase in Nusselt number indicates stronger convection and better heat exchanger performance.

4.4 Reynolds Number

$$Re=\frac{\rho VD}{\mu}$$

Reynolds number determines the flow regime and strongly influences turbulence intensity and heat transfer.

4.5 Performance Evaluation Criterion (PEC)

To simultaneously evaluate heat transfer enhancement and pressure loss, the Performance Evaluation Criterion is often employed.

$$PEC=\frac{Nu/Nu_0}{(f/f_0)^{1/3}}$$

where

- (Nu_0)=Baseline Nusselt number
- (f_0)=Baseline friction factor

Values greater than one indicate successful enhancement.

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5. RESULTS AND DISCUSSION

Numerous experimental and numerical studies have demonstrated that passive enhancement techniques significantly improve thermal performance while maintaining acceptable pressure losses.

5.1 Effect of Helical Baffles

Helical baffles generate continuous spiral flow inside the shell, eliminating dead zones commonly observed with conventional segmental baffles.

Reported improvements include:

- Heat transfer coefficient increase: **20–40%**
- Pressure drop reduction: **10–25%**
- Fouling reduction
- Better shell-side temperature distribution

The continuous flow path minimizes recirculation regions and enhances convective heat transfer.[19]

5.2 Effect of Vortex Generators

Vortex generators create longitudinal vortices that continuously disturb thermal boundary layers.

Typical improvements include:

- Nusselt number increase: **15–35%**
- Heat transfer coefficient improvement: **20–30%**
- Thermal effectiveness enhancement

Although pressure drop increases slightly, the overall thermal performance factor remains favorable.

5.3 Effect of Nanofluids

Nanofluids exhibit superior thermal conductivity compared with conventional fluids.

Common nanoparticles include:

- Al_2O_3
- CuO
- TiO_2
- Graphene
- Carbon nanotubes

Experimental studies report:

- Thermal conductivity improvement: **10–25%**
- Heat transfer coefficient increase: **25–40%**
- Nusselt number enhancement: **20–35%**

However, increasing nanoparticle concentration beyond optimum values may increase viscosity and pumping power.[20]

Table 2. Performance Comparison of Passive Enhancement Techniques

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Enhancement Technique	Heat Transfer Improvement	Pressure Drop	Overall Performance
Helical Baffles	20–40%	Low	Excellent
Twisted Tape	15–30%	Moderate	Very Good
Vortex Generators	20–35%	Moderate	Excellent
Nanofluids	25–40%	Slight Increase	Excellent
Ribbed Tubes	10–25%	Moderate	Good

6. INDUSTRIAL APPLICATIONS

Modified heat exchangers incorporating passive enhancement techniques have found widespread application across numerous industrial sectors due to their ability to improve thermal efficiency, reduce energy consumption, and enhance system reliability. Continuous improvements in geometric design and advanced heat transfer fluids have enabled industries to achieve significant operational and economic benefits.

6.1 Power Generation

Thermal and nuclear power plants employ shell-and-tube heat exchangers in condensers, feedwater heaters, economizers, and cooling systems. The use of helical baffles and enhanced tube surfaces improves heat transfer while reducing fouling and pressure losses, thereby increasing plant efficiency and reducing maintenance requirements.[31]

6.2 Chemical and Petrochemical Industries

Chemical processing plants require efficient heat exchangers for reactors, distillation columns, condensers, and process cooling systems. Passive enhancement techniques improve temperature control, reduce energy consumption, and enhance process reliability under high-temperature and high-pressure operating conditions.

6.3 HVAC and Refrigeration Systems

Heating, Ventilation, Air Conditioning (HVAC), and refrigeration systems extensively utilize compact heat exchangers. Nanofluids and vortex generators have demonstrated considerable potential for increasing evaporator and condenser performance while reducing equipment size and compressor power consumption.[32]

6.4 Automotive Industry

Modern automobiles, hybrid vehicles, and electric vehicles employ heat exchangers for battery thermal management, engine cooling, intercoolers, and air-conditioning systems. Lightweight compact heat exchangers incorporating enhanced fins, vortex generators, and nanofluids improve thermal management and vehicle energy efficiency.

6.5 Renewable Energy Systems

Solar thermal collectors, geothermal systems, biomass plants, and waste heat recovery units increasingly utilize modified heat exchangers to maximize thermal energy utilization. Enhanced heat transfer directly improves renewable energy conversion efficiency and system sustainability.

6.6 Food and Pharmaceutical Industries

Food processing and pharmaceutical manufacturing require precise temperature control during pasteurization, sterilization, evaporation, and cooling

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operations. Modified heat exchangers improve thermal uniformity, reduce processing time, and enhance product quality while minimizing contamination risks.

Table 3. Industrial Applications of Modified Heat Exchangers

Industry	Major Application	Primary Benefit
Power Plants	Condensers, Feedwater Heaters	Higher thermal efficiency
Chemical Industry	Process Heat Recovery	Reduced energy consumption
HVAC	Air Conditioning, Refrigeration	Improved COP
Automotive	Radiators, Battery Cooling	Better thermal management
Renewable Energy	Solar Collectors, Waste Heat Recovery	Enhanced energy utilization
Food Processing	Pasteurization, Sterilization	Improved process efficiency

7. ADVANTAGES AND LIMITATIONS

7.1 Advantages

Passive heat transfer enhancement techniques provide several engineering advantages:

- Increased heat transfer coefficient.
- Higher Nusselt number.
- Improved thermal effectiveness.
- Reduced heat exchanger size.
- Lower operating costs.
- Enhanced energy efficiency.
- Reduced fouling tendency.
- Simple retrofitting of existing equipment.
- Minimal maintenance requirements.
- No external energy requirement.

These advantages make passive enhancement techniques economically attractive for both new installations and modernization of existing thermal systems.[33]

7.2 Limitations

Despite significant thermal improvements, several limitations remain:

- Increased manufacturing complexity for modified geometries.
- Additional pressure drop in some enhancement techniques.
- Higher pumping power at excessive turbulence levels.
- Nanofluid stability issues during long-term operation.
- Higher initial investment for advanced materials.
- Difficulty in cleaning certain enhanced surfaces.

Therefore, optimization should consider both thermal enhancement and hydraulic performance to ensure maximum overall system efficiency.

8. FUTURE PERSPECTIVES

Future research in heat exchanger modification is expected to integrate advanced materials, intelligent optimization techniques, and digital technologies to achieve even greater thermal performance.

Promising research directions include:

- Artificial Intelligence-assisted heat exchanger optimization.

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- Machine learning for thermal performance prediction.
- Additive manufacturing of complex heat transfer surfaces.
- Graphene-based and hybrid nanofluids.
- Bio-inspired heat exchanger geometries.
- Smart heat exchangers with embedded sensors.
- Digital Twin-based thermal system monitoring.
- Topology optimization for compact heat exchangers.
- Sustainable low-carbon thermal systems.
- Industry 5.0-enabled intelligent thermal management.[34]

The integration of Artificial Intelligence, Computational Fluid Dynamics, additive manufacturing, and advanced nanomaterials is expected to significantly transform future heat exchanger design, enabling adaptive, high-efficiency thermal systems with improved reliability and sustainability.

9. CONCLUSION

Heat exchangers remain indispensable components in modern thermal engineering systems, and improving their performance is essential for enhancing energy efficiency and reducing operational costs. This review highlights the effectiveness of passive heat transfer enhancement techniques, including helical baffles, vortex generators, twisted tape inserts, and nanofluids, in improving thermal performance without requiring external energy input. Experimental and CFD investigations consistently demonstrate significant improvements in heat transfer coefficient, Nusselt number, and overall thermal effectiveness with acceptable increases in pressure drop. Among the reviewed techniques, helical baffles and nanofluids exhibit the greatest enhancement potential owing to improved fluid mixing and higher thermal conductivity. Although challenges related to pressure loss, manufacturing complexity, and nanofluid stability remain, recent advances in computational modelling, artificial intelligence, and advanced materials are expected to further optimize heat exchanger performance. Overall, passive heat exchanger modification represents a practical, economical, and sustainable approach for improving industrial thermal systems and supporting energy-efficient engineering applications.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the research facilities provided by the Department of Mechanical Engineering, Rungta College of Engineering and Technology (RCET), Bhilai, and GDRCST Bhilai. The authors also thank the laboratory staff for their assistance with metallographic preparation, hardness testing, and XRD analysis. No external funding was received for this investigation.

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