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Numerical Investigation of Effect of Chevron Angle on Thermofluids Characteristics of Plate Heat Exchanger

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Abstract

This research examines the influence of 30° and 60° chevron angles on the thermofluid performance of plate heat exchangers, emphasizing critical parameters such the Nusselt number, friction factor, and overall heat transfer coefficient. The study indicates that utilizing water as the working fluid in a counter-flow arrangement, a 60° chevron angle markedly improves heat transfer efficiency relative to a 30° angle, chiefly owing to heightened turbulence. Nonetheless, this enhancement is accompanied by a significant increase in pressure decrease. The 30° chevron angle minimizes pressure loss, rendering it advantageous for applications that emphasize energy efficiency. These findings highlight the significance of chevron angle selection in enhancing performance according to particular application requirements. The research provides significant insights into optimizing heat transfer efficiency and minimizing pressure loss, informing future designs and operational strategies for plate heat exchangers across various industrial applications.

Keywords: Chevron Angle, Thermo-fluid Characteristics, Plate Heat Exchanger, Nusselt Number, Computational Fluid Dynamics (CFD)

1. Introduction

Heat exchangers are essential in industrial, commercial, and residential applications for transferring thermal energy between two fluids while maintaining their separation. They function by permitting one fluid to circulate within while another circulates externally around a thermally conductive surface, such as metallic plates or tubes, so enabling heat transfer. Heat exchangers can be categorized by design, fluid type, and heat transfer direction, with prevalent types including shell and tube, plate and frame, spiral, and regenerative. [1]

Shell and tube heat exchangers are extensively utilized in power plants and oil refineries because of their ability to manage substantial volumes and elevated pressures. Conversely, plate and frame heat exchangers are appropriate for low-volume applications, such as residential heating and cooling, in addition to chemical processing. These comprise superimposed metal plates that establish alternating flow channels for liquids. Their compact design and elevated surface area enhance heat transfer efficiency; however, pressure loss and gasket degradation may diminish performance over time. Chemical plate heat exchangers, a variant of plate heat exchangers, possess a distinctive plate configuration that induces turbulence, hence improving heat transfer efficiency. This design enhances performance but also results in increased pressure drops, necessitating greater energy for fluid circulation. Chevron plates are available in multiple profiles—triangular, trapezoidal, and sinusoidal, with the sinusoidal design being the most prevalent for optimizing efficiency and pressure. [2]

Chemical plate heat exchangers are utilized in various sectors, including HVAC systems, chemical processing, food and beverage production (such as pasteurization and sterilization), power generation, refrigeration, and waste heat recovery. Their efficacy, compactness, and versatility render them suitable for various applications. The parameters used in this study may be examined in experimental research, but it is not analyzed in numerical investigations which clarifies the novelty of this study.

1.2 Literature Review

Asadi et al. [3] assess the impact of chevron angle on thermal-hydraulic performance, including heat transfer coefficient, friction factor, and pressure drop. The friction factor was seen to grow with an upward chevron angle; however, at the ideal angle, the friction factor exhibits an inverse relationship with mass flow rate in both laminar and turbulent regimes. The ideal chevron angle was established at 60 degrees.

Qiao et al. [4] developed a novel model to analyze plate heat exchangers with single-phase or two-phase flow. The single-phase flow utilized water, whilst the two-phase flow employed a mixture of ammonia and R22. The model evaluates the effects of fluctuations in heat transfer and pressure drop on the mass flow distribution inside the channels. The findings indicated that the inaccuracy in heat load was below 5% for two-phase flow and below 2% for single-phase flow.

Muley et al. [5] did a study on a plate heat exchanger with single-phase flow, varying the chevron angles to 30º and 60º. The research indicated that both the chevron angle and the expansion factor substantially influence the pressure drop and heat transfer in the heat exchanger. The researchers noted an escalation in pressure loss and heat transmission. The 60º chevron angle produced a greater surface area and extended flow channel, resulting in enhanced turbulence and heat transmission.

Shiomi et al. [6] devised a chevron-type heat exchanger that functions with two-phase flow. The pressure drop across the heat exchanger in two-phase flow is a critical component influencing the system's efficiency. The researchers discovered that the pressure loss escalates with an increase in the corrugation angle of the plates within the heat exchanger.

Guan-min et al. [7] performed a numerical simulation investigation to examine the flow fields between two corrugated plates with differing corrugation inclination angles. The research examined the influence of the Chevron angle on the flow dynamics between the corrugated plates. The simulation findings demonstrated that the Chevron angle significantly influences the flow behavior between the corrugated plates.

2. Description and Design

2.1 Chevron type plate

Chevron plates produce considerable turbulence, improving heat transfer efficiency. Their heat transfer coefficients can equal those of tubes with Reynolds numbers five times greater. The corrugations of chevron plates facilitate turbulent flow and enhance durability under elevated pressure. This study investigates the influence of chevron angles on friction and heat transfer coefficients, considering the prevalence of chevron configurations.

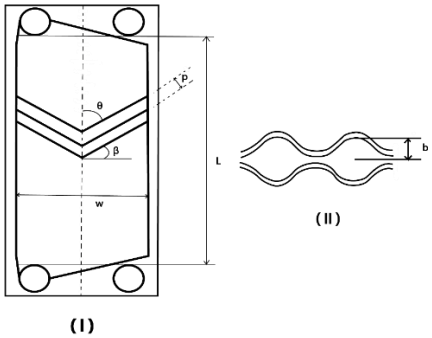


Fig. 1. (I) Schematic representation of a chevron plate; (II) corrugation dimension

2.2 Description of heat transfer method and terms

The overall heat transfer coefficient (U) of a Chevron-type plate heat exchanger can be determined using the Log Mean Temperature Difference (LMTD) method. The LMTD approach assumes a constant temperature difference between the hot and cold fluids throughout the heat exchanger.

$$LMTD = \frac{(\Delta T_1 - \Delta T_2)}{Ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}, \qquad Q = \dot{m} \times C_p \times \Delta T \tag{1}$$

$$Re = \frac{\rho * v * Dh}{\mu}, \qquad \mathrm{Dh} = \frac{2\mathrm{b}}{\Phi}, \qquad \gamma = \frac{2b}{P} \tag{2}$$

Where b is the inner-plates distance and Φ is the area enlargement factor and here γ is the channel aspect ratio

$$\Phi = \frac{1}{6}\left\{1 + \left[1 + \left(\frac{\pi}{2cos\beta}\right)^2 \gamma^2\right]^{0.5} + 4\left[1 + \left(\frac{\pi}{2\sqrt{2}cos\beta}\right)^2 \gamma^2\right]^{0.5}\right\} \tag{3}$$

Here β= (90º - θ) and For θ = 30º and 60º respectively

$$Nu = 0.093 Re^{0.716} Pr^{1.3} \left(\frac{\mu}{\mu s}\right)^{.14}, \qquad Nu = 0.112 Re^{0.716} Pr^{1.3} \left(\frac{\mu}{\mu s}\right)^{.14} \tag{4}$$

$$f = \frac{\Delta P \times D_h}{2 \times L \times \rho \times u^2} \tag{5}$$

where Nu is Nusselt Number, Re is Renoylds Number, Pr is Prandtl number and f is frictional factor.

3. Methodology

This work used Computational Fluid Dynamics (CFD) for numerical analysis, which consists of three phases: pre-processing, computation, and post-processing. In the pre-processing phase, the 3D geometry and grid are created, integrating fluid properties inside a rectangle domain. ANSYS Workbench R19.2 software is utilized to create an unstructured 3D tetrahedral mesh with variable element sizes to guarantee precise outcomes. Mesh dependency analysis is performed to verify that the numerical findings are independent of mesh size and appropriately reflect fluid dynamics. This guarantees that the outcomes derived from the numerical analysis are dependable and precise. Figure 2 illustrates the flow diagram of the process.

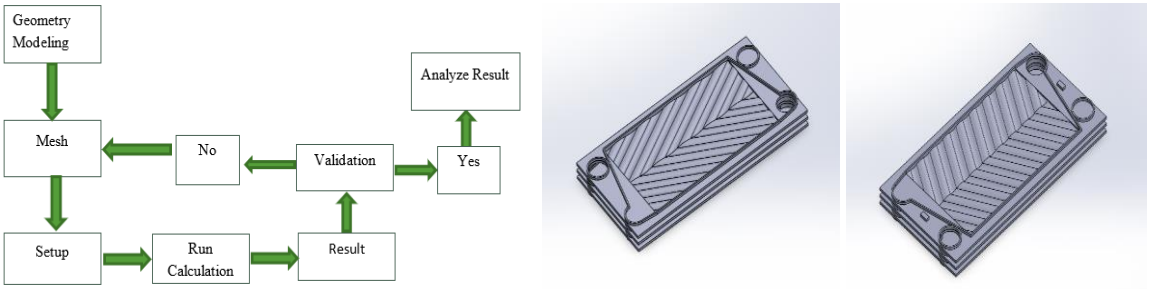


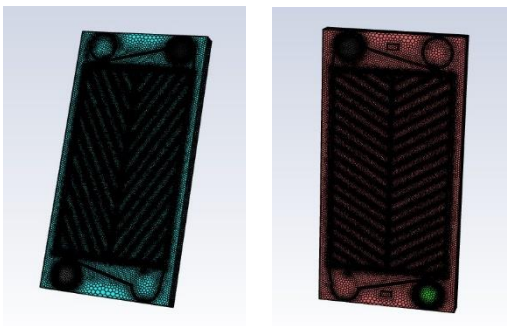
Fig. 2. Flowchart of methodology and Geometry Model for 30° and 60° Plate Heat Exchanger

Table 1. Geometrical parameters of the Model

Serial No.	Description	Dimension
01	Plate Length (L_T) *mm*	250
02	Plate Width (W_T) *mm*	116
03	Longitudinal distance between ports (L) *mm*	186
04	Transverse distance between ports (W) *mm*	110
05	Plate thickness (t) *mm*	0.6
06	Port diameter (D) *mm*	25
07	Corrugation pitch (p) *mm*	9

3.1 Mesh Generation

The research utilized Computational Fluid Dynamics (CFD), which was segmented into pre-processing, computation, and post-processing phases. During the pre-processing phase, ANSYS Workbench R19.2 was utilized to create an unstructured three-dimensional tetrahedral mesh with inflation layers. A mesh dependence analysis was performed to verify that result correctness remained unaffected by mesh size. An unstructured polyhedral mesh was generated for the 30º chevron angle, featuring surface mesh sizes ranging from 0.28 (minimum) to 6.5 (maximum), a growth rate of 1.2, and a maximum skewness of 0.86. Three boundary layers with a transition ratio of 0.272 were incorporated, yielding a total of 1,585,111 cells with a minimum orthogonal quality of 0.08. For the 60º chevron angle, analogous parameters were employed, featuring surface mesh sizes of 0.28 (minimum) and 6.4 (maximum), a maximum skewness of 0.85, and three boundary layers. This yielded 1,478,455 cells, with a minimum orthogonal quality of 0.08. Critical surfaces, such as the inlet, outlet, and heat exchanger body, were designated for boundary condition assignment and post-processing.



(a) (b)

Fig. 3. Mesh generation for Chevron plate heat exchanger (a) 30° , (b) 60°

Table 2. Boundary Conditions and simulation settings

SI No.	Factors	Considerations
01	Fluid	Water
02	Flow Condition	Steady-state
03	Inlet	Velocity Inlet
04	Outlet	Pressure outlet
05	Cold Water Inlet Velocity	0.001 m/s to 0.01 m/s
06	Hot Water Inlet Velocity	0.001 m/s to 0.01 m/s
07	Cold Water Inlet Temperature	30ºc
08	Hot Water Inlet Temperature	100ºc
09	Convergence Factor	1e-6

3.2 Mesh Dependency

Mesh independence guarantees uniform simulation outcomes irrespective of mesh dimensions. A convergence analysis optimizes the mesh until satisfactory accuracy is attained, balancing resolution and computing expense. This work achieved mesh independence with 2,048,237 elements, guaranteeing physically accurate results.

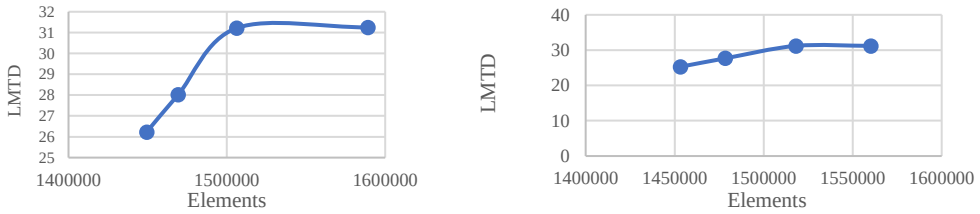


Fig. 4. Mesh dependency of 30° and 60° chevron plate heat exchanger

4. Result and Discussion

The research demonstrates that the chevron angle markedly affects the thermofluid efficiency of plate heat exchangers, highlighting considerable variations between 30° and 60° arrangements. The 60° chevron angle exhibits increased heat transfer efficiency, defined by an elevated total heat transfer coefficient and Nusselt number, signifying improved convective heat transfer between fluids. This enhancement arises from heightened turbulence, which amplifies thermal contact. Nonetheless, this advantage entails specific compromises. The friction factor, indicative of resistance to fluid flow, is markedly elevated in the 60° arrangement, resulting in augmented pressure decreases and elevated energy consumption for pumping. These variables result in increased operational expenses, which must be taken into account in energy-sensitive applications. In contrast, the 30° chevron angle provides diminished frictional resistance and decreased pressure drops, leading to enhanced energy efficiency and lower pumping power demands. This arrangement is better suited for applications that prioritize reduced operational costs above optimal heat transfer efficiency. Nonetheless, the diminished turbulence at the 30° angle results in inferior heat transfer rates relative to the 60° configuration. The results underscore the significance of meticulous chevron angle selection in heat exchanger design. Engineers must evaluate the trade-offs between improved heat transmission and heightened energy requirements. In applications where optimizing heat transfer is essential, the 60° angle is advantageous, although increased pressure losses. Conversely, for energy-efficient operations, the 30° angle provides a more equitable solution by diminishing pumping power demands. Subsequent research should concentrate on investigating other chevron angles, corroborating numerical findings with experimental tests, and refining other design parameters like as plate spacing and flow rate. This equitable strategy can improve performance and operational efficiency across several industrial applications.

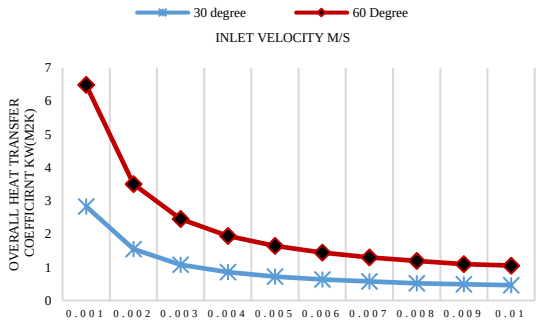


Fig. 5. Overall heat transfer coefficient vs inlet velocity for 30º and 60° chevron plate heat exchanger

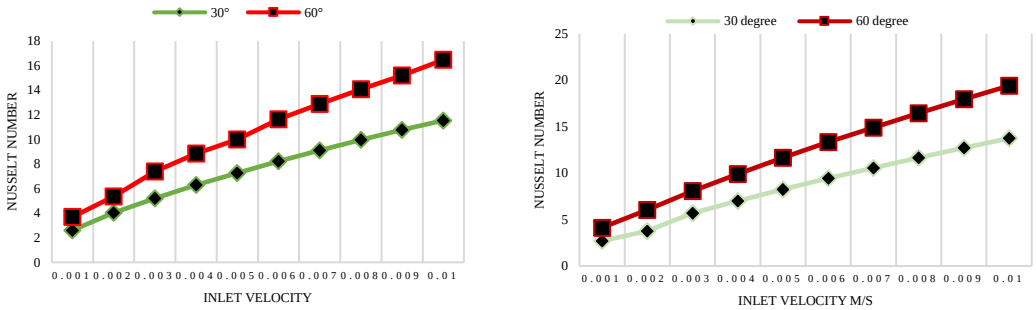


Fig. 6. Nusselt number vs inlet velocity for chevron plate heat exchanger (hot and cold fluid volume)

The research indicates that a 60º chevron angle in plate heat exchangers enhances heat transfer while also elevating flow resistance, resulting in increased energy losses and greater pumping power demands. Consequently, determining the ideal chevron angle necessitates a balance between heat transfer efficiency, pressure drop, and energy expenditures.

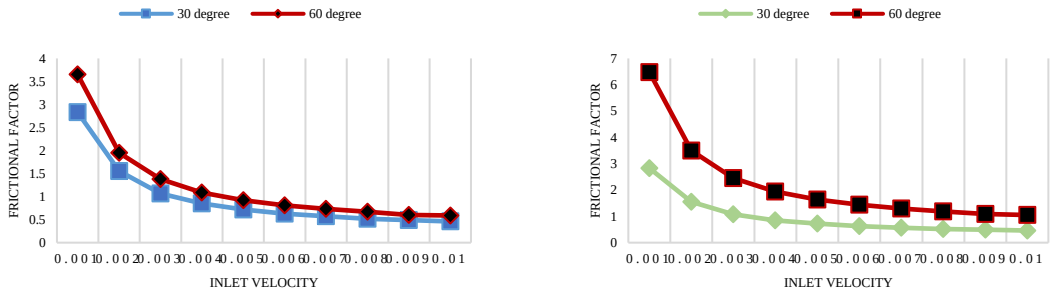


Fig. 7. Frictional factor vs inlet velocity for chevron plate heat exchanger (cold and hot fluid volume)

The pressure and temperature contours from the numerical modeling of chevron heat exchangers correspond closely with experimental measurements, exhibiting smooth and evenly dispersed patterns. The contours distinctly illustrate the flow behavior, facilitating the evaluation of the influence of chevron angles on heat transfer and pressure drop, hence offering significant insights into performance.

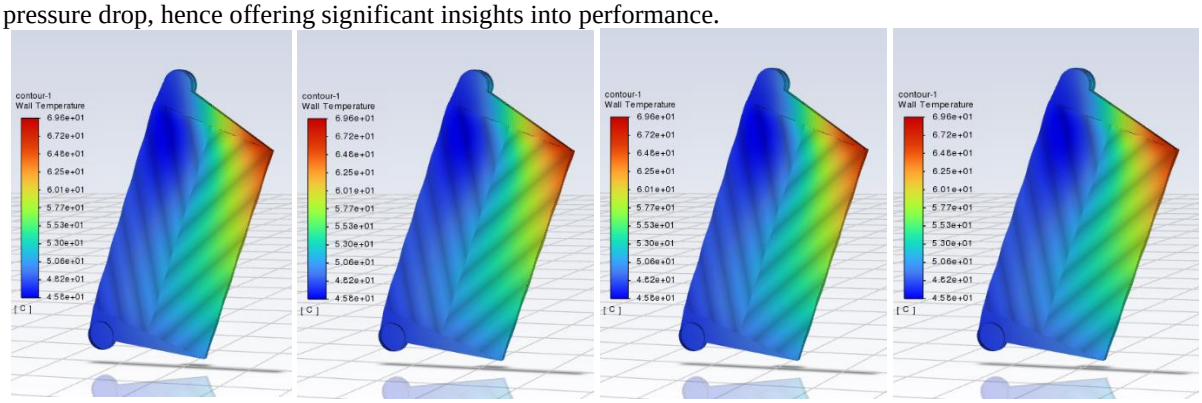


Fig. 8. Temperature contours for chevron plate heat exchanger at 0.001 m/s (cold and hot fluid volume)

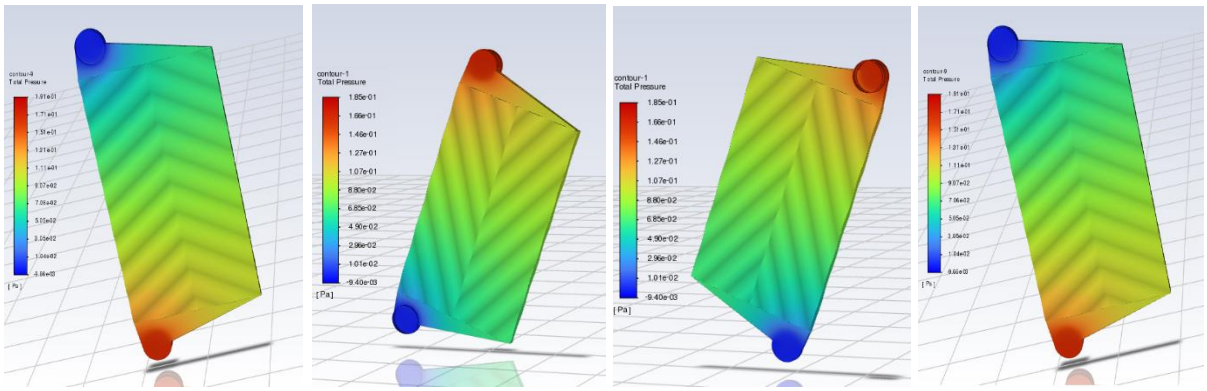


Fig. 9. Pressure contours for chevron plate heat exchanger at 0.001 m/s (cold and hot fluid volume)

The research demonstrates that a 60º chevron heat exchanger has superior thermofluid performance compared to a 30º angle, attributable to enhanced turbulence and heat transfer efficiency. Nonetheless, specific constraints may influence precision:

- **Modeling assumptions:** Oversimplified assumptions, such as disregarding temperature-dependent material properties and fluid compressibility, can result in mistakes.
- **Variations in material properties:** Constant thermal characteristics were presumed, although they may fluctuate in reality, influencing outcomes.
- **Turbulence model:** The employed k-epsilon turbulence model may inadequately represent turbulent flow, and more sophisticated models could provide enhanced accuracy.
- **Grid resolution:** Although an optimum grid was employed, finer grids may enhance precision.

The enhanced thermofluid properties of the 60º angle have practical uses, improving energy efficiency and reducing costs in sectors such as chemical processing, power generation, refrigeration, and food processing.

5. Conclusion

The investigation indicates that chevron angles markedly affect the thermofluid efficiency of plate heat exchangers. The 60° chevron angle improves heat transfer rates by augmenting turbulence, rendering it optimal for applications where thermal efficiency is critical. This advantage entails an increased pressure drop, necessitating greater energy for fluid circulation. The 30° chevron angle reduces pressure loss, providing an energy-efficient solution for applications where minimizing operational expenses is essential. These findings underscore the significance of choosing the optimal chevron angle to equilibrate heat transfer efficiency and pressure drop based on particular requirements. Subsequent research ought to examine a wider array of chevron angles, corroborate numerical data through empirical studies, and assess supplementary design variables such as plate spacing and flow rate. These insights establish a basis for enhancing heat exchanger design, augmenting energy efficiency, and minimizing operational expenses across diverse industrial applications. There are some future research suggestions:

- Investigate alternative chevron angles to enhance comprehension of their influence on performance.
- Experimental verification to substantiate the numerical findings.
- Enhance additional design factors, such as plate spacing and flow rate, to achieve improved equilibrium.
- Extend the findings to additional forms of heat exchangers, including shell-and-tube configurations.
- Examine additional fluid parameters (e.g., viscosity, density) to augment comprehension of thermofluid dynamics.

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