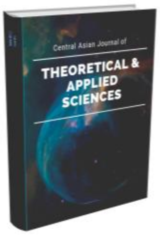

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Article

A Review On Improve The Operation of Heat Exchangers

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Abstract: Heat exchange plays an important role in various industrial applications, where their performance dating directly affects energy efficiency, operating costs and stability. This review examines strategies to increase the operation of heat exchangers, focus on design improvement, advanced materials, control functions and maintenance techniques. Important factors affecting performance, such as heat transfer efficiency, faucer, pressure drop and flow events, are analyzed. Design modifications, including expanded surfaces, microchans and nanostractor coatings, are discussed to improve the heat transfer rate. In addition, advanced control strategies, such as PID setting, forward control and AI-based adaptive controls are investigated for better regulation and stability. The use of height demonstration materials, anti -free coatings and future maintenance techniques further enhance the reliability and life. Smart monitoring, self -cleaning surfaces and future progress in hybrid energy systems are expected to revolutionize the performance of heat exchangers, which can reduce the energy consumption and the environmental impact.

Keywords: heat exchange, thermal efficiency, PID control, forward control, adaptive control, fouling, advanced materials, future indication Maintenance, energy adjustment

1. Introduction

Heat exchange is important in the chemical industry, especially widely used shell-end pipe models, which facilitate cooling efficient heating or process fluids. Important operating parameters include the input and output temperature (setting point), as well as the input and output flow rate, which requires process stability to maintain the outlet temperature at the desired setting point. To achieve accurate control, a classic PID (proportional-intelligent) is originally used in a response control loop to regulate system performance. However, in order to further increase the command response and reduce external disorders, a forward control is integrated with the PID controller, making a common control strategy for better efficiency. Various performance indices are evaluated to compare the stability of only feedback on feedback-FEED-FURVED Control Loops, while auto-tuning of PID controllers is used and the system is simulated to adapt to system responsibility [1]. In addition, in order to include intelligent decisions and adaptability, an unclear logic control (FLC) has been proposed as an advanced alternative to traditional PID methods, which provide increased strength and flexibility. This review emphasizes the importance of integrating classic and intelligent control techniques, and emphasizes the role of foreign compensation, auto-tuning and unclear logic control in adapting heat exchanger performance in industrial applications [2].

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Effective energy use promises a permanent future to constantly increase energy needs. High energy efficiency refers to energy savings and environmental garden. The Heat Exchang Network (HEN) process is an essential part of the adaptation for integration, especially for energy -intensive industries such as chemical, petroleum and power generation. The purpose of hen retrofitting is to reduce external energy requirements and increase the energy efficiency of the system. In addition, reduction in emissions and minimization of footprints is also contributed by chicken equipment. The combination of chicken with organic rankin cycle or thermal energy storage provides flexible control and control of the energy system with significant energy saving. The created network process provides a practical understanding of the system and reflects the Nexus of materials, energy and equipment. Meanwhile, the cost of retrofitting is another concern. The trade -off between heat extraction and capital investment is important for the choice of retrofitting. [3]

There are two primary chicken retrofitting methods: pinch -based method and mathematics -based method [4]. The pin -based method with solid thermodynamic background was first proposed by Tjoe and Linnhoff [5]. The original pinch method shows the energy characteristics of the process flows. Visualization of graphic tools, such as mixed curves (CCS) and Grand Composite Curves (GCCS) [6] as the pinch method, can provide the energy measurement method. CCS composes available heat (hot streams) and required heat (cold streams) at the same time. All streams are included in a warm power curve and a cold current curve. To ensure sufficient use levels, the minimum method is transmitted to CCS according to the temperature ΔTmin. The GCC is then manufactured from the offset CCs by calculating bags and painting the heat pockets. Since power data is composed of CCS and GCCS, the heat recovery distribution is not performed. But for a retrofitting problem, the heat load has already been assigned to the current hen, making CCS and GCCs inadequate for this condition. For better chicken retrofitting, modified grid diagrams are developed.

Literature Review

Heat Exchanger Systems and Their Industrial Significance

Heat exchangers are essential components in various industrial processes, particularly in the chemical industry, where they facilitate efficient heat transfer for heating or cooling fluids. The shell-and-tube heat exchanger is among the most commonly used models due to its robust design, ease of maintenance, and high thermal efficiency. The effectiveness of heat exchangers depends on key operational parameters, including input and output temperatures, flow rates, and heat transfer coefficients. Several studies have focused on improving heat exchanger performance through optimization techniques, material advancements, and enhanced control strategies.

Heat exchange is important in industrial applications, but they introduce many challenges that affect performance, energy efficiency and operating costs [7]. One of the primary problems is to optimize heat exchanges by reducing energy waste and improving general efficiency. The heat transfer reduces the efficiency by interfering with the flow of heat on the surfaces, making the problem more complicated with scaling and mineral deposits. To solve these challenges, industry strategies are used, such as using advanced materials, performing regular maintenance and changing the flow direction to reduce fauting [8]. In addition, improvement of energy efficiency is a significant focus for companies aimed at reducing carbon footprint. Recovery of incompetent heat from process flows increases unnecessary energy waste and operating expenses. To combat this, the industry integrates more heat exchanges to catch and redirect waste heat, leading to increasing general energy use and stability [9].

Reliable and cost -effective heat exchanger solutions have led to progress in design adaptation, material selection and control strategies. Complex heat exchanger configurations must be suitable for separate fluid properties, but can reduce inability from inappropriate size and inappropriate types of heat exchanges, increase in energy consumption and system. Considering their important role in industries such as chemical processing, power generation and plumbing systems, heat exchange is necessary to ensure efficient heat transfer while maintaining fluid properties. They contribute to general efficiency, by adapting energy use, improving product quality and promoting sustainable industrial practice. Frequent challenges such as fabinating, energy -giving boundaries and subptimal designs conduct research and innovation. To solve these problems, the industry quickly adopts advanced calculation modeling, better content and intelligent control systems to increase the performance and credibility of heat exchanger[10].

Changing thermal energy in mechanical strength in steam turbines or optimizing combustion efficiency in power plants. In the chemical industry, they regulate the response temperature and ensure the quality and process stability of the product[11]. Similarly, in cooling and plumbing systems, facilitating heat exchange temperature control, increasing energy efficiency and operating efficiency. The basic principle of heat transfer through a solid wall or conductive surface ensures minimal fluid mixture while maintaining the integrity of each medium. This ability is important for industries that depend on accurate thermal control to adapt to performance, reduce energy consumption and increase stability. By restoring effectively and reusing waste heat, heat exchange plays an important role in reducing operating costs and reducing environmental impact, making them indispensable in modern industrial applications[12].

2. Materials and Methods

2.1 Classical PID Control in Heat Exchangers

The PID (Proportional-Integral-Derivative) controller is widely used in process industries for regulating the temperature and flow rates in heat exchangers. Classical PID control operates within a feedback control loop to maintain the desired set-point temperature by adjusting system inputs based on error signals. Researchers have investigated different tuning methods, including Ziegler-Nichols, Cohen-Coon, and auto-tuning algorithms, to enhance the stability and response time of PID controllers. While PID controllers offer reliable performance, their effectiveness is often limited in handling external disturbances and nonlinear system behavior, necessitating the integration of additional control strategies.

Heat exchange are important components of industrial operation, which facilitates effective heat transfer, while maintaining the integrity of fluid currents in processes such as cooling, heating and thermal regulation. Their role is fundamental in industries, including energy production, chemical production and cooling, where effective heat exchange is necessary to reduce performance adjustment and energy consumption. Heat exchanges work through a solid wall by transferring heat from a lower temperature from a high subordinate fluid or conducting the surface, and preserving the quality and properties of each medium to ensure minimal fluid interaction. This mechanism increases industrial efficiency by enabling recovery of waste heat and reuse, reducing operating costs and environmental impacts.

One of the most widely used heat exchanges in the industry is the shell-end heat exchanger, preferred by its versatility, ability to withstand high pressure and easy maintenance. Compared to double pipe heat exchange, the Shell-End pipe systems provide a ratio of high heat transfer from the surface from volume, making them more effective in different industrial applications. Their design has a bunch of pipes attached inside a cylindrical shell, where one liquid flows through the pipes and the other flows around them in the shell. These heat exchanges are often found in power generation, plumbing systems, chemical processing and production industry, due to their ability to handle a wide range of operating conditions.

Despite their benefits, heat exchange introduces many challenges, including faucer, restrictions on energy recovery and design inhibition. Belling occurs when unwanted deposits accumulate on heat transfer surfaces, reduce efficiency and increase energy consumption. Scaling, corrosion and mineral deposits increase this problem, and require regular maintenance and advanced material applications to reduce the effects. In addition, optimization of energy recovery is important for industries aimed at reducing carbon footprint. Disabled heat recovery can lead to excessive energy waste and operating expenses, which can be motivated to capture and rebuild the waste heat more efficiently for the integration of many heat exchanges**.**

3. Results and Discussion

To increase the performance of heat exchanger, advanced control strategies have been detected. Traditional PIDs (proportional-centramplary-intercurs) controllers have been widely used to regulate the outlet temperature of heat exchange. However, they often show high overruns, which can cause instability [13], [14]. To reduce these problems, forward control is incorporated with PID controllers, reaction accuracy is improved. Further adaptation is achieved using internal model -based controls (IMC), where a mathematical model of the process goes parallel to the real system. The IMC-based controls have gained popularity due to their ability to reduce overshadowing and determine time, which has improved stability and control efficiency[15].

The PID controller, widely used in industrial automation, controls processes through its three components: proportional (P), integral (I) and derived (D) control. Proportional control responds to the current error by applying an improvement in the order of magnitude, the response is improved in time, but fails to eliminate faults in stable state. Integrated control addressed it by depositing the previous errors and adjusting the output, eliminating effectively displacement errors, but causing potential fluctuations and instability. The derivative control increases stability by predicting future errors based on their speed, reduces overshadows and improves soaking, although it may be very sensitive to noise. In the heat exchanger application, the PID controller regulates the expiry temperature to maintain process stability, but the standard PID control often has overruns, fluctuations and long decided at times. To reduce these problems, the forward control is linked to PIDs to improve reaction accuracy by explaining external disorders, while internal model-based PID increases the setting stability, reduces overrun and receives rapid settlement time. These advanced control strategies adapt to the heat exchanger performance by ensuring accurate thermal regulation, reducing energy waste and improving process efficiency. The study evaluates classic PIDs, forward PIDs and internal model-based controls, and compares their efficiency in adaptation with thermal process control for industrial heat exchanger systems[16].

Recently, progression detects thermodynamics -based control strategies to increase the efficiency of heat exchangers, providing an alternative for traditional methods. For example, previous studies have enforced thermodynamic principles, which have used thermodynamic principles to design concentrations Pipe exchange and sliding mode control for systems that transfer energy to fluids from electrical resistance. In this context, the proposed approach introduces a strong regulatory strategy that benefits from thermodynamically basics. In particular, an output error is defined in correlation with total entropy production, which forms the basis for geometric controllers designed with a high-ranking supervisor and an anti-windup scheme. This controller is tested to track temperature references, and performance is compared to a classic PID controller, which shows possible benefits of thermodyics-based control in system stability, energy efficiency and the general improvement of the process.Recently, progression detects thermodynamics -based control strategies to increase the efficiency of heat exchangers, providing an alternative for traditional methods. For example, previous studies[17] have enforced thermodynamic principles, which have used thermodynamic principles to design concentrations Pipe exchange and sliding mode control for systems that transfer energy to fluids from electrical resistance. In this context, the proposed approach introduces a strong regulatory strategy that benefits from thermodynamically basics. In particular, an output error is defined in correlation with total entropy production, which forms the basis for geometric controllers designed with a high-ranking supervisor and an anti-windup scheme. This controller is tested to track temperature references, and performance is compared to a classic PID controller, which shows possible benefits of thermodyics-based control in system stability, energy efficiency and the general improvement of the process[18].

The classic PID controller Setting Methods in Literature include tests and wrong methods, Zigler-Nechaol's step response method (Taylor Instrument Company in 1941 and 1942, developed in the United States), Zigler-Nachol's Frequency Response Method, Relay Adaptation Method and Cohen-Kainen[19]. Further research, such as Veng Khen Ho et al. , (Ise[20]), and under the Integral Time Absolute Err (Itae) calculation load disorder. In addition, as the procedure increased from fatal to time-continuous conditions from 0.1 to 1, the phase margin improved from 30 ° to 60 °, while the setting sources adapted to the SET point response received about 2 at about 2 and the advantage margins of about 2 and the profit margin. These formulas are mainly dependent on the PID controller zero so that the poles in the process can be canceled. Classic setting methods, while implementing rapid calculations work under specific opinions on plant and desired production. They try to remove analytical or graphic process features to determine controlling settings, but often require setting beyond the initial stages due to the underlying boundaries in their beliefs.

Figure 1 illustrates the block diagram of a process control system using a classical PID (Proportional-Integral-Derivative) controller. The diagram shows the flow of information in a closed-loop system where the controller compares the process output with the setpoint and adjusts the control input to minimize the error. This feedback mechanism is essential in maintaining stable operation in heat exchangers by regulating temperature or flow rate.

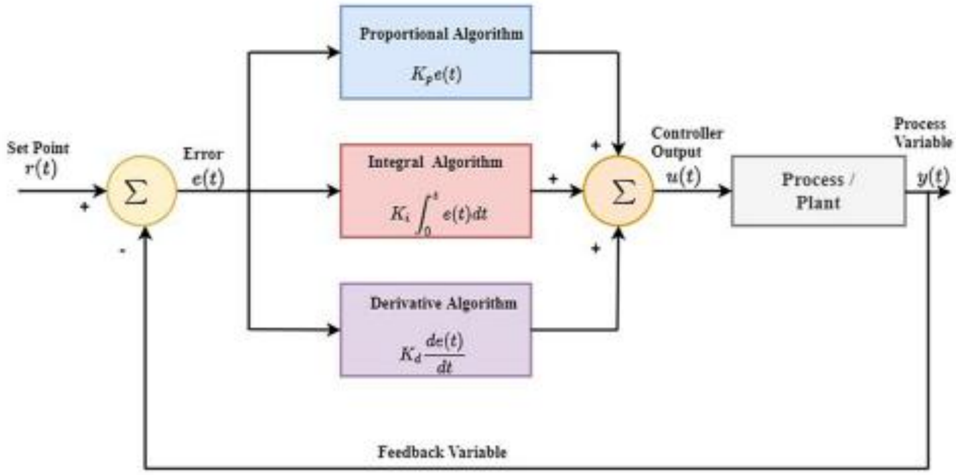

Figure 1. Block diagram of process control using PID

3.1 Enhanced Control Strategies: Feed-Forward and Hybrid Approaches

To improve the dynamic response of heat exchangers, feed-forward controllers have been introduced alongside PID controllers. The feed-forward approach anticipates disturbances and compensates for them before they affect the system, thereby enhancing overall stability. Hybrid control systems that combine feedback and feed-forward mechanisms have demonstrated improved transient response and reduced temperature fluctuations in heat exchangers. Several studies have explored the effectiveness of model-based predictive control (MPC) and adaptive control techniques in optimizing heat exchanger operations, providing a more robust solution compared to traditional PID control.

Hybrid control approaches, which integrate multiple control strategies, have attracted significant attention to their ability to adapt the performance under different operating conditions. For example, a combination of prominent control of proportional-anthrgral type (PID) or unclear logic control (FLC) increases the strength of the system by taking advantage of future abilities and adaptive learning. Advanced applications, hybrid controllers include machine learning algorithms, Model Predictive Control (MPC) or reinforcement learning techniques that adjust the dynamic control parameters. These approaches have been implemented with success in industrial automation, motor vehicle systems and energy management, where accurate control and adaptability are important[21].

3.2 Literature review based on fuzzy management for hybrid vehicles

The limitations of classical PID and hybrid controllers in handling complex and nonlinear heat exchanger systems have led to the exploration of intelligent control techniques, such as fuzzy logic and artificial intelligence (AI)-based approaches. Fuzzy logic controllers (FLCs) have been implemented to enhance adaptability and decision-making by mimicking human reasoning, providing more precise control over heat exchanger operations. Additionally, machine learning and deep learning models have been applied to predict temperature variations and optimize control strategies, offering promising results in improving efficiency and reducing energy consumption. Recent research has highlighted the potential of AI-driven control systems to revolutionize heat exchanger operations, making them more adaptive and self-optimizing.

The literature review process has been carried out systematically, considering recently published papers. The steps involved in the literature review are presented in a flowchart, as shown in Fig. 1. In [22], a Fuzzy Logic Controller (FLC) was proposed for a parallel Hybrid Electric Vehicle (HEV) to balance battery charge, enhance drivability, and reduce NOx emissions. In [23], an Intelligent Energy Management Agent (IEMA) combined with a driving condition-based FLC was developed for efficient power distribution, with simulations on the Urban Dynamometer Driving Schedule (UDDS) and nine other drive cycles demonstrating its effectiveness for parallel HEVs. In [24, 25], a novel approach using FLC for controlling engine power and speed in a power-split HEV was introduced, incorporating fuzzy gain scheduling for dynamic PI controller tuning. In [26], an FLC-based system optimization method was designed, considering input parameters such as power demand, vehicle speed, and State of Charge (SoC), employing numerical optimization algorithms and fuzzy set theory [27] to enhance efficiency. In [28], a fuzzy multi-objective optimization technique was used to convert motor energy into fuel consumption metrics for a parallel HEV. In [29], a rule-based algorithm utilizing FLC for a plug-in parallel HEV demonstrated improved efficiency, with reduced SoC depletion rates and fuel consumption compared to traditional rule-based methods. In [30], a predictive Energy Management System (EMS) incorporating FLC and reinforcement learning for a parallel HEV based on velocity data was introduced. In [31], an intelligent genetic algorithm-optimized FLC was proposed, utilizing engine target torque, demanded torque, and battery SoC as inputs, with the torque distribution coefficient between the Electric Motor (EM) and Internal Combustion Engine (ICE) as the output. Experimental results confirmed that this control strategy ensures balanced battery charging and discharging, minimizes fuel consumption, mitigates peak torque production, reduces emissions, and enhances overall vehicle performance. Finally, in [32], an improved self-tuning fuzzy proportional-integral controller was proposed for HEV applications. Figure 2 presents a flowchart outlining the structured methodology followed in the literature review process for heat exchanger optimization. The steps include problem identification, data collection from academic databases, classification of research themes (such as classical PID control, hybrid control, and fuzzy logic), followed by critical analysis and synthesis. This diagram helps visualize how the review was conducted systematically and supports the transparency and reproducibility of the review process. It is particularly useful for readers seeking to replicate or understand the research framework.

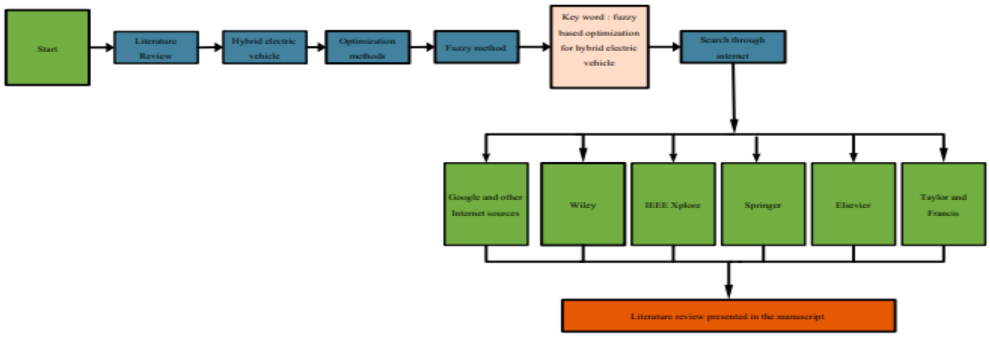

Figure 2. Flowchart representing the process of literature review

Table 1 presents a comparative summary of advanced strategies aimed at improving the operational performance of heat exchangers. Each strategy is described along three dimensions: the type of improvement, the method used, and the practical benefits. For example, enhanced heat transfer surfaces such as corrugated tubes and fins increase thermal exchange rates, while nanofluids improve fluid thermal conductivity. The integration of intelligent control systems like PID and feed-forward loops enhances regulation accuracy and energy savings.

Improvement Strategy	**Description**	**Benefits**
Enhanced Heat Transfer Surfaces	Use of fins, corrugated tubes, or surface coatings to improve heat transfer efficiency.	Increases heat transfer rate, reduces required surface area.
Optimized Flow Arrangements	Counterflow, crossflow, and multi-pass designs to maximize thermal efficiency.	Enhances heat exchange, improves temperature control.
Advanced Materials	Use of high thermal conductivity materials such as aluminum or copper alloys.	Improves heat conduction, increases durability.
Fouling Reduction Techniques	Chemical cleaning, surface coatings, and self-cleaning mechanisms to prevent fouling.	Maintains efficiency, reduces maintenance downtime.
Use of Nanofluids	Employing nanoparticles in working fluids to enhance thermal properties.	Improves heat transfer coefficient, increases overall efficiency.
Integration of Control Systems	Implementation of PID, feed-forward, or model-based control strategies.	Enhances process stability, reduces energy consumption.
Energy Recovery Systems	Utilizing waste heat recovery units such as economizers or regenerative exchangers.	Reduces energy loss, improves overall system efficiency.

Table 1: Strategies to Improve the Operation of Heat Exchangers, summarizing different methods for enhancing heat exchanger performance.

4. Conclusion

Heat exchange are important components of industrial processes, which facilitates effective heat transfer in different applications. This review has examined different types of heat exchanges, with special emphasis on the design of shell-end pipes due to extensive use and operational benefits. Various control strategies, including classic PID controllers, foreign mechanisms and advanced hybrid methods, have been analyzed for their efficiency in adapting to the performance of heat exchanger. While classic setting methods such as Ziglar -nachols and Cohen -Koon offer easy implementation, they often require further refining to achieve optimal control.

Integration of thermodynamics -based control strategies and intelligent control systems presents a promising direction to improve the efficiency of heat exchanger. Advanced control technique helps to reduce overruns, increase stability and reduce energy loss. However, challenges such as the system that are not linearity, fautting and operational uncertainties affect performance. To address these problems through adaptive control systems can further improve the reliability and efficiency of the heat exchanger system, which can make them more durable and cost -effective in industrial applications.

The future of heat exchanger optimization lies in integrating advanced control strategies, intelligent automation, and innovative materials to enhance performance, reliability, and sustainability. Artificial intelligence (AI) and machine learning (ML) can revolutionize predictive maintenance by enabling real-time fault detection, performance monitoring, and adaptive control, while model predictive control (MPC) and reinforcement learning-based controllers offer self-tuning capabilities to optimize efficiency under dynamic operating conditions. Additionally, the development of high-performance materials with superior thermal conductivity and fouling resistance can significantly improve heat exchanger durability, and the incorporation of nanofluids as working fluids presents a promising approach to enhancing heat transfer rates. In the context of sustainable energy systems, future research should focus on optimizing heat exchangers for renewable energy applications such as solar thermal power plants, geothermal systems, and waste heat recovery, where maximizing energy efficiency is crucial. Moreover, the integration of Internet of Things (IoT)-based smart monitoring solutions will enable real-time performance assessment, remote diagnostics, and autonomous control, reducing operational costs and minimizing downtime. As industries move toward greener technologies, advancements in control methodologies, material science, and intelligent monitoring systems will drive the next generation of heat exchangers, making them more efficient, adaptive, and environmentally sustainable for industrial, commercial, and residential applications.

REFERENCES

[1] Padhee, Subhransu, Yuvraj Bhushan Khare, and Yaduvir Singh. "Internal model based PID control of shell and tube heat exchanger system." In Students' Technology Symposium (TechSym), 2011 IEEE, pp. 297-302. IEEE, 2011.

[2] Tabatabaee, Sajad, Pegah Roosta, Mokhtar Sha Sadeghi, and Alireza Barzegar. "Fuzzy PID controller design for a heat exchanger system: The energy efficiency approach." In Computer Applications and Industrial Electronics (ICCAIE), 2010 International Conference on, pp. 511-515. IEEE, 2010.

[3] Li, N., Wang, J., Klemeš, J. J., Wang, Q., Varbanov, P. S., Yang, W., ... & Zeng, M. (2021). A target-evaluation method for heat exchanger network optimisation with heat transfer enhancement. Energy Conversion and Management, 238, 114154.

[4] Klemeš, J. J., Wang, Q. W., Varbanov, P. S., Zeng, M., Chin, H. H., Lal, N. S., ... & Walmsley, T. G. (2020). Heat transfer enhancement, intensification and optimisation in heat exchanger network retrofit and operation. *Renewable and Sustainable Energy Reviews*, *120*, 109644.

[5] Asante, N. D. K., & Zhu, X. X. (1997). An automated and interactive approach for heat exchanger network retrofit. *Chemical Engineering Research and Design*, *75*(3), 349-360.

[6] Yong, J. Y., Varbanov, P. S., & Klemeš, J. J. (2015). Heat exchanger network retrofit supported by extended Grid Diagram and heat path development. *Applied Thermal Engineering*, *89*, 1033-1045.

[7] Heat Exchanger Market Size, Share & Trends Analysis Report By Product (Plate & Frame (Brazed, Gasketed, Welded), Shell & Tube, Air Cooled), By End-use, By Region, And Segment Forecasts, 2023 – 2030 https://www.grandviewresearch.com/industry-analysis/heatexchangers-market

[8] A. H. Elsheikh et al, "Applications of Heat Exchanger in Solar Desalination: Current Issues and Future Challenges," Water, vol. 14, (6), pp. 852, 2022. Available: https://www.proquest.com/scholarlyjournals/applications-heat-exchanger-solardesalination/docview/2642661778/se-2. DOI: https://doi.org/10.3390/w14060852.

[9] M. Lipnický and Z. Brodnianská, "Enhancement of Heat Dissipation from the Hydraulic System Using a Finned Adaptive Heat Exchanger," Applied Sciences, vol. 13, (9), pp. 5479, 2023. Available: https://www.proquest.com/scholarlyjournals/enhancement-heat-dissipation-hydraulicsystem/docview/2812407318/se-2. DOI: https://doi.org/10.3390/app13095479.

[10] A. Bhattad et al, "Thermal Performance Evaluation of Plate-Type Heat Exchanger with Alumina–Titania Hybrid Suspensions," Fluids, vol. 8, (4), pp. 120, 2023. Available: https://www.proquest.com/scholarly-journals/thermal-performanceevaluation-plate-type-heat/docview/2806532797/se-2. DOI: https://doi.org/10.3390/fluids8040120.

[11] M. Sibtain, H. Liang, M. R. Uddin, M. A. Mond, A. A. Ansari and M. Z. U. Khan, "Investigating the Heat Transfer Characteristics of Finprolonged Heat Exchanger for Waste Heat Recovery," 2023 14th International Conference on Mechanical and Intelligent Manufacturing Technologies (ICMIMT), Cape Town, South Africa, 2023, pp. 234-237, doi: 10.1109/ICMIMT59138.2023.10201099.

[12] A. Heydari et al., "An investigation of multi-parameters effects on the performance of liquid-to-liquid heat exchangers in rack level cooling," 2023 22nd IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (ITherm), Orlando, FL, USA, 2023, pp. 1-5, doi: 10.1109/ITherm55368.2023.10177525.

[13] Orlando Duran et.al, "Neural Networks for Cost Estimation of Shell and Tube Heat Exchangers, " in Proc. IntI Multi Corif- Eng. Com put. Scient., vol II, pp. 1584-1589, Mar 2008.

[14] Anton Sodja et.al, "Some Aspects of Modeling of Tube-and-Shell Heat-Exchangers," in Proc of 7th Modelica Corif-, Italy, pp. 716- 721, Sep 2009.

[15] Padhee, S., Khare, Y. B., & Singh, Y. (2011, January). Internal model based PID control of shell and tube heat exchanger system. In *IEEE Technology Students' Symposium* (pp. 297-302). IEEE.

[16] Subhransu Padhee, Yuvraj Bhushan Khare, Yaduvir Singh "Internal Model Based PID Control of Shell and Tube Heat Exchanger System," IEEE, JAN 2011.

[17] J. P. García-Sandoval, Towards the control principles of heat exchangers based on thermodynamic, in: Memorias del Congreso Nacional de Control Automático, CNCA, 2021, pp. 80-85.

[18] M. Pérez-Pirela, J. García-Sandoval, O. Camacho, Development of a simplified model for a distributed-parameter heat exchange system for thermodynamic principles-based control purposes, IFAC-PapersOnLine 51 (2018) 396-401. doi:https://doi.org/10.1016/j.ifacol. 2018.07.311, 2nd IFAC Conference on Modelling, Identification and Control of Non-linear Systems MICNON 2018.

[19] Ziegler John G, Nichols Nancy B (1942) Optimum settings for automatic controllers. J Dyn Syst Meas Control Trans ASME 115:220-222

[20] Åström KJ, Hägglund T (1984) Automatic tuning of simple reg-ulators. IFAC Proc Vol 17(2):1867-1872

[21] Mittal, P., Raghu, N., & Sharma, K. (2015). Tuning Optimization of Hybrid controller for temperature control of heat exchanger by Gradient Descent method. Transfer, 30, 1.

[22] Lee H, Koo E, Sul S, Kim J (2000) Hyeoun-Dong Lee, Euh-Suh Koo, Seung-Ki Sul, and Joohn-Sheok Kim, pp 33-38

[23] Won J, Langari R, Member S (2005) Intelligent energy manage-ment agent for a parallel hybrid vehicle-Part II: torque distribu-tion. Charge Sustenance Strateg Perform Results 54:935-953

[24] Syed FU, Kuang ML., Smith M et al (2009) Fuzzy gain-scheduling proportional-integral control for improving engine power and speed behavior in a hybrid electric vehicle. IEEE Trans Veh Tech-nol 58:69-84

[25] Ippolito L, Loia V, Siano P (2003) Extended fuzzy c-means and genetic algorithms to optimize power flow management in hybrid electric vehicles. Fuzzy Optim Decis Mak 2:359-374. https://doi.org/10.1023/B:FODM.0000003954.49357.63

[26] Mashadi B, Emadi SAM (2010) Dual-mode power-split trans-mission for hybrid electric vehicles. IEEE Trans Veh Technol 59:3223-3232
[27] Wu L, Wang Y, Yuan X, Chen Z (2011) Multiobjective optimiza-tion of HEV fuel economy and emissions using the self-adap-tive differential evolution algorithm. IEEE Trans Veh Technol 60:2458-2470
[28] Liu YZH (2012) Fuzzy multi-objective control strategy for paral-lel hybrid electric vehicle. IET Electr Syst Transp 2:39-50. https ://doi.org/10.1049/iet-est.2011.0041
[29] Ming L, Ying Y, Liang L et al (2017) Energy management strategy of a plug-in parallel hybrid electric vehicle using fuzzy control. Energy Procedia 105:2660-2665. https://doi.org/10.1016/j.egypr 0.2017.03.771
[30] Liu T, Hu X, Li SE, Cao D (2017) Reinforcement learning opti-mized look-ahead energy management of a parallel hybrid electric vehicle. IEEE/ASME Trans Mechatron 22:1497-1507
[31] Dawei M, Yu Z, Meilan Z, Risha N (2017) Intelligent fuzzy energy management research for a uniaxial parallel hybrid electric vehicle. Comput Electr Eng 58:447-464. https://doi.org/10.1016/j. compeleceng.2016.03.014
[32] Yadav AK, Gaur P (2016) An optimized and improved STF-PID speed control of throttle controlled HEV. Arab J Sci Eng 41:3749-3760. https://doi.org/10.1007/s13369-016-2131-5