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INTEGRATION OF FOURIER SERIES, ARTIFICIAL INTELLIGENCE AND SMART SENSORS IN HVAC THERMAL ANALYSIS: A SYSTEMATIC LITERATURE REVIEW

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Abstract. HVAC (Heating, Ventilation, and Air Conditioning) systems play a crucial role in maintaining thermal comfort, air quality, and energy efficiency in buildings. This study aims to examine the contribution of Fourier series in HVAC thermal analysis and the integration of artificial intelligence (AI) and smart sensors to support energy optimization.The method used was a Systematic Literature Review (SLR) of scientific publications from 2019 to 2025 obtained from the ScienceDirect, IEEE, MDPI, and Academia databases. Articles that met the inclusion criteria were analyzed based on their objectives, methodologies, and research results, then grouped thematically. The results of the study showed that Fourier series are effective in representing periodic temperature signals, simplifying data complexity, and improving thermal prediction accuracy. Meanwhile, the integration of AI and smart sensors enables real-time responses, improved energy efficiency, and thermal comfort stability. The main challenges identified include limitations in experimental validation, the complexity of integrating Fourier–AI–sensors into a single framework, and the high computational requirements for large-scale implementation. Thus, it can be concluded that this study contributes to mapping current approaches and recommending research directions for the development of more efficient, adaptive, and sustainable data-driven and intelligent computing-based HVAC systems.

Keywords: fourier series, energy efficiency, HVAC, artificial intelligence, smart sensors

Abstrak. *Sistem HVAC (Heating, Ventilation, and Air Conditioning) memiliki peran krusial dalam menjaga kenyamanan termal, kualitas udara, dan efisiensi energi bangunan. Penelitian ini bertujuan untuk mengkaji kontribusi deret Fourier dalam analisis termal HVAC serta integrasi kecerdasan buatan (AI) dan sensor pintar guna mendukung optimasi energi. Metode yang digunakan adalah Systematic Literature Review (SLR) terhadap publikasi ilmiah periode 2019–2025 yang diperoleh dari basis data ScienceDirect, IEEE, MDPI, dan Academia. Artikel yang memenuhi kriteria inklusi dianalisis berdasarkan tujuan, metodologi, dan hasil penelitian, kemudian dikelompokkan secara tematik. Hasil kajian menunjukkan bahwa deret Fourier efektif dalam merepresentasikan sinyal suhu periodik, menyederhanakan kompleksitas data, dan meningkatkan akurasi prediksi termal. Sementara itu, integrasi AI dan sensor cerdas memungkinkan respons real-time, peningkatan efisiensi energi, serta stabilitas kenyamanan termal. Tantangan utama yang diidentifikasi meliputi keterbatasan validasi eksperimental,*

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kompleksitas integrasi Fourier–AI–sensor dalam satu kerangka kerja, dan kebutuhan komputasi tinggi untuk implementasi skala besar. Sehingga dapat disimpulkan bahwa studi ini memberikan kontribusi berupa pemetaan pendekatan terkini dan rekomendasi arah penelitian untuk pengembangan sistem HVAC berbasis data dan komputasi cerdas yang lebih efisien, adaptif, dan berkelanjutan.

Kata kunci: *deret fourier, efisiensi energi, HVAC, kecerdasan buatan, sensor cerdas*

1. Introduction

HVAC (heating, ventilation, and air conditioning) systems play an important role in improving air quality and maintaining thermal safety and energy efficiency in various building environments [1]. One of the main challenges in HVAC management is understanding and predicting recurring temperature patterns, which are influenced by daily rhythms, seasonal changes, and building occupant activities. Therefore, accurate mathematical analysis is essential [2].

Fourier series is an efficient mathematical approach for representing recurring temperature variations. By decomposing the temperature signal into a number of harmonic components, this approach provides more accurate predictive and control capabilities for thermal behavior in HVAC systems [3]. This approach demonstrates that Fourier series are effective in reducing the complexity of temperature signals and support adaptive control based on mathematical simulation [4].

With the development of digital technology, mathematical methods such as Fourier series are now supported by the application of artificial intelligence (AI) and smart sensors, which significantly improve the analysis and response capabilities of the system [5]. This combination of technologies enables HVAC systems to accurately predict temperatures and respond to environmental changes in real time [6].

The research by Yayla et al [7] shows that the application of artificial intelligence (AI) in HVAC systems can save at least 10% of energy consumption while increasing the level of thermal comfort for occupants. These results show that the proposed method has great potential as a useful tool for sustainable development, while also functioning as an autonomous control mechanism that becomes increasingly effective as its performance improves.

This systematic literature review (SLR) aims to identify, categorize, and summarize recent research that integrates Fourier series, artificial intelligence (AI), and smart sensors in HVAC system thermal analysis. This study makes an important contribution by providing a comprehensive mapping of the methods that have been applied, identifying existing research gaps, and suggesting directions for future innovation in data-driven and computational intelligence-based HVAC technology.

2. Research Methods

This study uses a qualitative approach with the Systematic Literature Review (SLR) method. The main objective of this study is to examine the contribution of Fourier series in modeling heat distribution in HVAC systems and to evaluate the application of artificial intelligence (AI)-based sensor technology in improving thermal control accuracy. This study was conducted in November 2025. The literature collection and analysis process was carried out online through access to international scientific databases. The research subjects were scientific articles relevant to the study topic, namely the application of Fourier series in HVAC thermal analysis and the integration of AI-based smart sensors. The articles reviewed were from peer-reviewed publications between 2019 and 2025, obtained from databases such as ScienceDirect, IEEE Xplore, Academia, and MDPI. The research procedure includes the following stages:

1. Identification and collection of articles from predetermined databases
2. Selection of articles based on inclusion and exclusion criteria (Table 1)
3. Systematic review of article content, including methodological classification (experimental, numerical, theoretical).
4. Comparative analysis between the Fourier series approach, CFD simulation, and AI-based sensor data.
5. Synthesis of findings to identify heat distribution patterns, system efficiency, and HVAC response to environmental conditions.

Table 1. Inclusion and exclusion criteria for article selection

Criteria	Inclusion	Exclusion
Document type	Scientific journal articles that have undergone peer review	Non-peer-reviewed articles, such as opinion blogs or unofficial proceedings
Language	Written in English	Articles in languages other than English
Publication Year	Published between 2019 and 2025	Articles published before 2019-2025 or after 2025
Research topic	Fourier series, HVAC thermal analysis, sensor and AI technology	Topics outside of thermal analysis or not relevant to HVAC systems
Research focus	Numerical studies, mathematical modeling, integration of AI and sensors in HVAC	Studies that do not involve Fourier series or smart sensor technology

- Inclusion Criteria

The inclusion criteria in this study were established to ensure that the selected articles were relevant, credible, and aligned with the research objectives. The articles included in this review were peer-reviewed scientific journal publications written in English and published between 2019 and 2025. The selected studies focused on the application of Fourier series in thermal analysis, particularly in HVAC systems, and involved the integration of smart sensors and artificial intelligence technologies. In addition, only research articles that employed numerical analysis, mathematical modeling, or computational approaches in HVAC-related thermal studies were considered. All included articles were required to be available in full text to allow an in-depth evaluation of their methodologies and findings.

- Exclusion Criteria

The exclusion criteria were applied to eliminate studies that did not meet the required academic and thematic standards. Articles that were not peer-reviewed, including opinion papers, editorials, blogs, and unofficial conference proceedings, were excluded from the review. Publications written in languages other than English or published outside the 2019 - 2025 time range were also excluded. Furthermore, studies that were not directly related to thermal analysis or HVAC systems were omitted. Articles that did not involve the use of Fourier series, smart sensors, or artificial intelligence techniques in their analysis were not considered in this study.

Data analysis was conducted qualitatively using a thematic approach. Selected articles were analyzed to identify the contribution of Fourier series in thermal modeling, the effectiveness of AI sensor integration, and research gaps that could be exploited for the development of new methods. The selection process was visualized in a PRISMA (Preferred Reporting Items for Systematic review and Meta-Analyse) flow diagram in Figure 1.

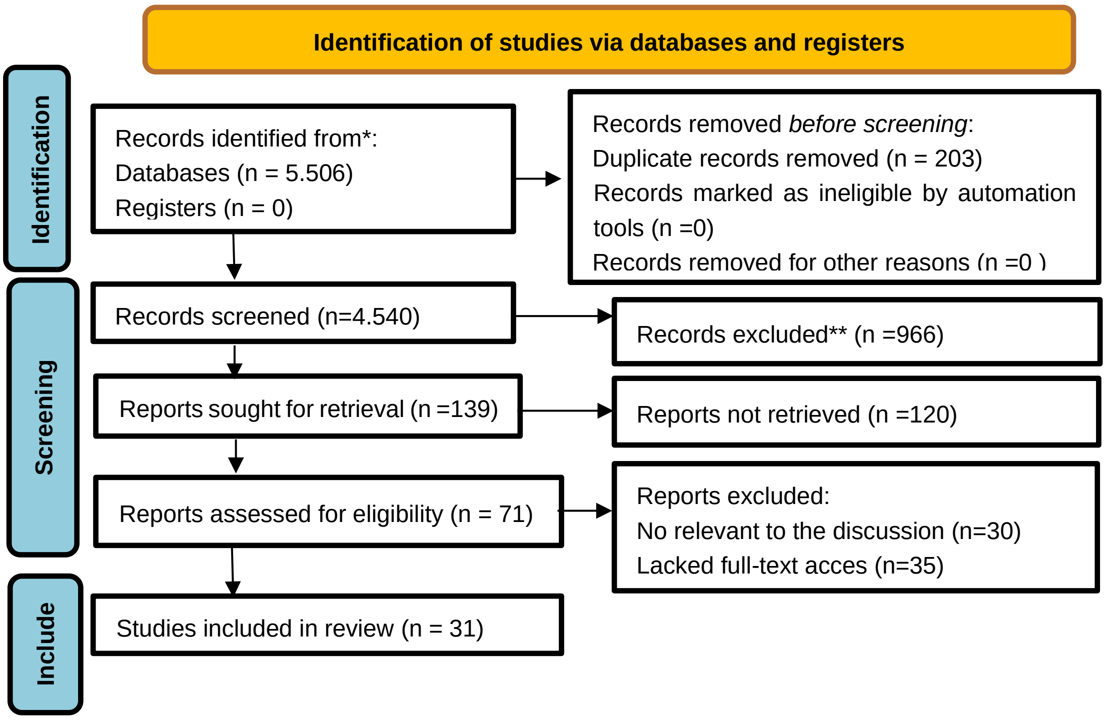

Figure 1. PRISMA flow diagram

3. Result and Discussion

Based on the selection process and thematic analysis, a number of articles were identified as being highly relevant to the focus of this study. The following Table 2 summarizes the main characteristics of the articles analyzed, including the focus of the study, methods, and important findings related to the integration of Fourier, AI, and sensors in thermal systems.

3.1 Trends in the Use of Fourier Series in HVAC

Based on a literature review, a notable trend is the integration of demand response (DR) strategies into HVAC scheduling frameworks. For example, the application of hybrid LSA-ANN and PSO-ANN frameworks to optimize the "On/Off" scheduling of household appliances[14]. Javaid et al., [15] used a neuro-fuzzy method to regulate home energy loads and costs, which was proven to increase efficiency when ToU electricity rates were applied in summer and winter. Meanwhile, Zhou et al., [16] combined ANN load prediction with MPC and dynamic programming to optimize active and efficient energy management.

Figure 2 depicts the detailed HVAC system diagram of the FRP-2 data set includes several HVAC operating scenarios, including heating, cooling, and economizer modes. Specifically, the basic heating scenario reflects the standard heating mode without advanced control intervention. The data set for this scenario is provided in CSV file format. This file contains high-resolution measurements recorded every minute over several days, providing sufficient detail for both short-term and long-term forecasting [17].

Table 2. Summary of Characteristics of Analyzed Articles

No	Author	Research Focus	Research method	Type of research	Research design	Key findings
1.	[8]	Efficiency of temperature monitoring with IoT-based sensor variations	Quantitative experiment	IoT-based temperature monitoring	Sensor variations: Thermostat, Thermistor (NTC/PTC), RTD, Thermocouple	The monitoring system works well; the average difference between sensors is only 0.07 degrees Celsius; calibration is necessary for optimal results.
2.	[9]	The role of Fourier series in mathematics and signal theory	Prakseolo analysis (ATD)	Fourier series ini matematics & signal theory	Comparative analysis of praxeology (basic mathematics, advanced mathematics, signal theory)	There are differences in motivation, techniques, and justifications between mathematics and signal theory, indicating a connectivity gap between theory and application.
3.	[10]	AI approach to HVAC energy management	Systematic Literature Review (2018-2025)	AI-based HVAC energy management	Algorithms (ML, DL, RL, GAN, multiagent systems	AI can reduce energy consumption by up to 40%; RL-based methods for multizone control; identification of research gaps and future directions
4.	[11]	Introduction to the theory and application of Fourier series and Fourier transforms	Theoretical studies, mathematica l analysis	Fourier series and Fourier transform	Trigonometric and exponential representation s, applications to periodic and aperiodic functions	Fourier analysis is effective for signal decomposition; real-world applications in signal processing, seismology, and physics.
5	[12]	Application of Fourier series to solve partial differential equations (heat equation)	Theoretical studies, numerical methods (finite difference, Fourier expansion)	Fourier analysis for PDEs (heat equation)	Derivation of Fourier coefficients, convergence discussion, Gibbs phenomenon, application to heat equation with inhomogeneou s boundary conditions	Fourier series are effective for solving the heat equation; numerical methods (finite difference & FFT) provide consistent approximate solutions.
5.	[13]	The future of AI, IoT, and cloud-based HVAC systems	Literature review & trend analysis	AI, IoT, and cloud-based HVAC	Integration of IoT sensors, AI algorithms, and cloud platforms	Future HVAC systems will be more automated, efficient, and sustainable; challenges include data security and integration costs.

Fourier series can mathematically describe periodic temperature patterns and form the basis for accurate thermal control. However, in order for this signal to be converted into adaptive decisions, a predictive model that learns from historical data is required.

Therefore, the integration of AI with Fourier analysis is important for creating smarter and more efficient HVAC systems.

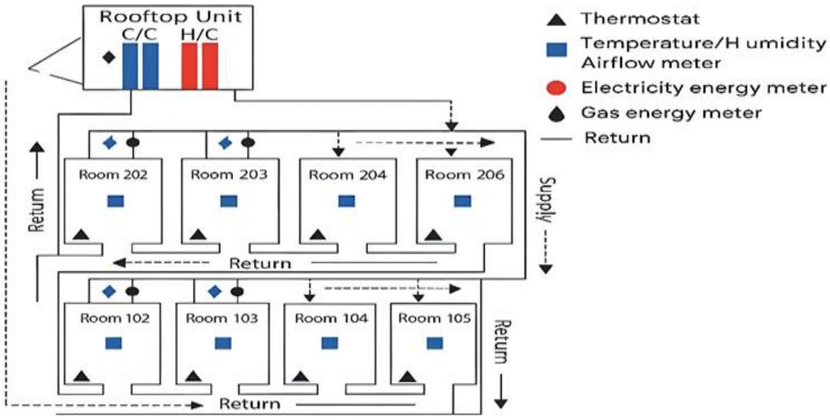

Figure 2. HVAC system diagram in the Fiber Reinforced Polymer (FRP-2)building, including sensor placement and control logic in various test settings [17]

3.2 AI Integration in HVAC Systems

The integration of smart control systems is now an important part of modern buildings, as buildings are becoming more complex and require direct control over various factors such as temperature, humidity, the number of people in a room, outdoor weather conditions, and the use of renewable energy [18]. As the needs of modern buildings become more complex, various digital solutions are being developed to improve energy efficiency and operational performance [19]

In an effort to realize this capability, various approaches in artificial intelligence have begun to be implemented, one of which is machine learning (ML), which enables systems to learn from historical data to identify patterns and make decisions automatically [20]. Furthermore, there is deep reinforcement learning (DRL), which is capable of developing adaptive control policies through a feedback-based iterative learning process [10]

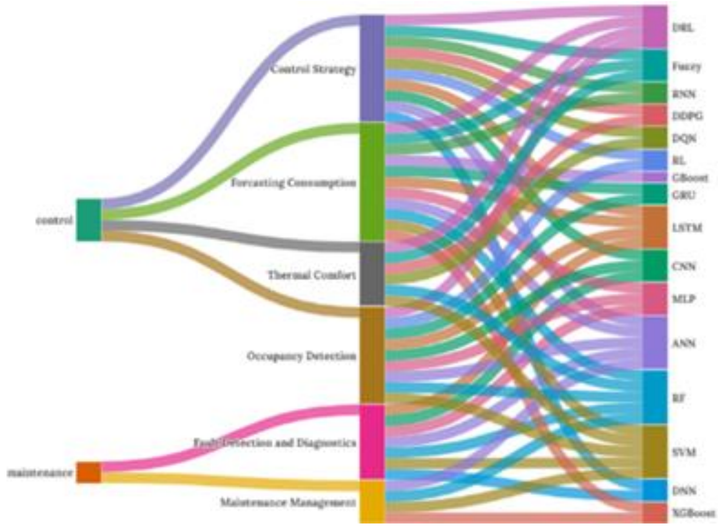

Figure 3. Sankey diagram between AI methods, techniques, and algorithms

The Sankey diagram (Figure 3) illustrates the relationship between AI methods, techniques, and algorithms used in HVAC systems for energy management. This visualization emphasizes the dominance of deep reinforcement learning (DRL) and machine learning (ML) in control, which has been proven effective in improving energy efficiency and operational reliability [10].

Although AI can create adaptive controls from previous data, the results depend on the quality of the input data. In thermal systems, raw data without frequency processing is less effective for recognizing time patterns. Therefore, smart sensors are very important for providing real-time data that supports the combination of physical models, AI algorithms, and current environmental conditions.

3.3 The Role of Smart Sensors

Sensors play an important role in HVAC systems by providing thermal comfort for building occupants. Sensors such as those based on the Internet of Things (IoT) and Building Automation Systems (BAS) can increase energy efficiency, reduce operating costs, and maintain optimal thermal comfort [21]. In smart HVAC systems, one type of sensor is the IoT, which functions as a data acquisition layer that provides real-time input for AI decision-making systems.

The types of IoT sensors used include:

1. Temperature and humidity sensors: measure room thermal parameters.
2. CO_2 and air quality sensors: to ensure air circulation and comfort.
3. Occupancy sensors (PIR/thermal cameras): detect human presence in a room.
4. External weather sensors/API: to monitor outdoor weather conditions such as temperature, solar radiation, and rainfall [22].

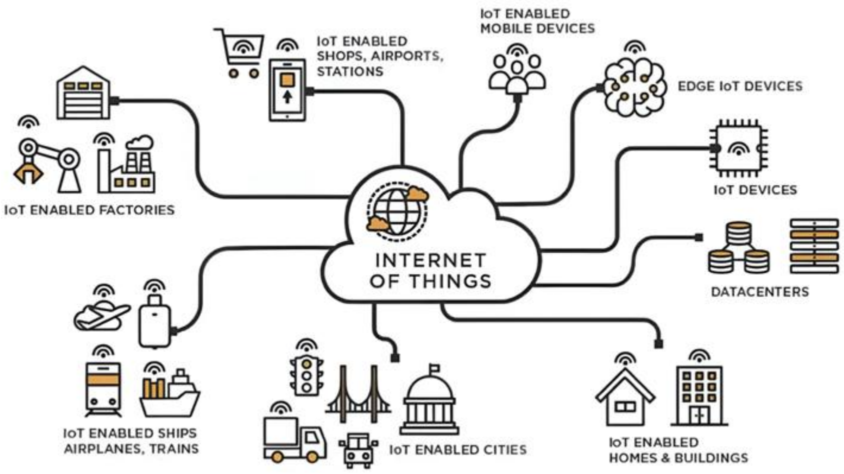

Figure 4. Model system internet of things (IoT) [23].

Figure 4 illustrates the Internet of Things (IoT) system model, showing the interconnection of various devices, sensors, and infrastructures through the internet. This model highlights how data is collected from different environments, such as smart buildings, cities, industrial facilities, mobile devices, and transmitted for further processing to support intelligent monitoring and control systems.

Smart HVAC systems are generally built with three main layers. The Sensor Layer collects data on temperature, humidity, CO_2, occupancy, and weather from sensors and APIs. This data is processed in the AI Processing Layer using ML algorithms to predict cooling or heating requirements. The results of the analysis are then executed by the

Control Layer, which carries out commands such as activating fans, opening dampers, or adjusting the AC temperature set point [24].

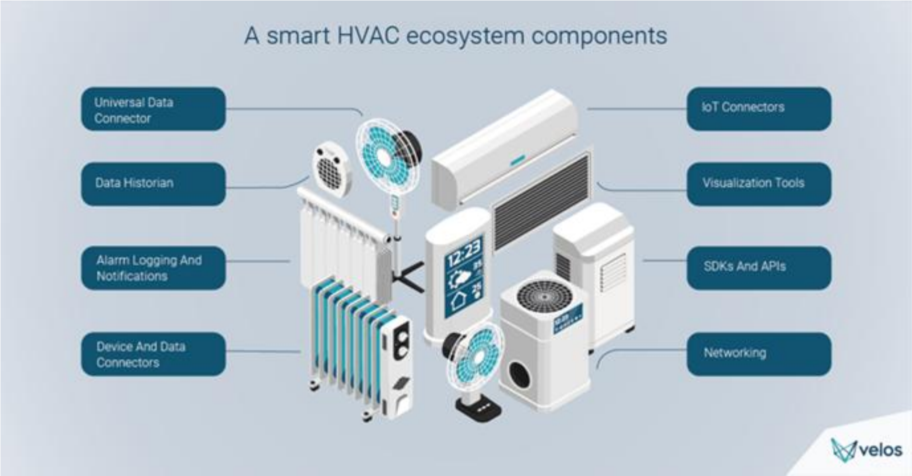

Figure 5. Model system smart HVAC [23]

Figure 5 illustrates the smart HVAC system model, highlighting the key components that form an integrated ecosystem for data acquisition, communication, and control. The model shows how HVAC devices are connected through data connectors, IoT interfaces, and networking infrastructure, enabling real-time monitoring, data processing, and intelligent system management.

Building Automation System (BAS) is a centralized system used to monitor and control building subsystems such as HVAC, lighting, and security. BAS functions as an execution layer, which implements AI predictions into actual actions.

Figure 6. Building automation system (BAS) model [23]

Figure 6 illustrates the Building Automation System (BAS) model, showing the centralized control of multiple building subsystems such as HVAC, lighting, indoor air quality, energy management, and security. This model emphasizes the role of BAS as an execution and coordination layer that translates high-level control strategies and AI-based decisions into operational actions within the building.

BAS works through integration with communication protocols such as BACnet, Modbus, or KNX, which enable AI commands (e.g., changing the temperature set point) to be executed automatically by the physical HVAC system. BAS also stores operational data that can be used for retraining AI algorithms (data logging). The main advantage of integrating AI and BAS is the ability to form a closed loop: sensor data → AI analysis → HVAC control → evaluation → readjustment [25]

Smart sensors not only provide real-time data, but also serve as a link between the physical world and digital decision-making systems. Through input from IoT and BAS sensors, thermal data can be further processed-for example, with Fourier transformation-before being utilized by AI models. However, the integration of these three main components (Fourier, AI, and sensors) into a holistic framework is still rare. This situation opens up opportunities for more comprehensive literature reviews to highlight research gaps and develop data-driven hybrid systems.

3.4 Literature Synthesis and Research Gap Identification

Based on a systematic review of the approaches used in the current literature, significant developments and research gaps can be identified in the context of data-based HVAC system modeling and optimization [26].

3.4.1 Mapping of Approaches That Have Been Used

A number of studies have utilized Fourier series as a method for modeling periodic temperatures in HVAC systems. For example, Hua et al. [27] developed complex-modeling with Fourier transform (CFT) for rapid simulation of transient energy transport. This approach has proven to be more efficient than the finite difference method, with visualization results in the form of temperature contours in the spatial-temporal domain.

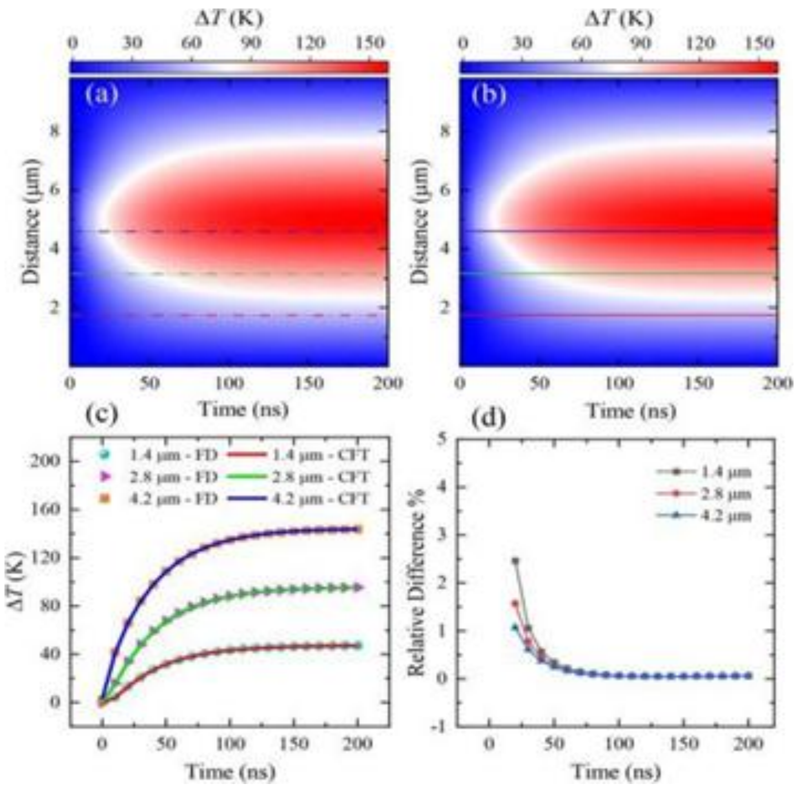

Figure 7. shows a comparison of temperature distributions between traditional numerical methods (a) and CFT (b), demonstrating high consistency with relative differences <5% (c and d) [27].

Figure 7 presents a comparison of temperature distributions obtained using traditional numerical methods and the CFT approach, illustrating the spatial–temporal evolution of temperature contours and their level of agreement.

On the other hand, artificial intelligence (AI)-based approaches, particularly Fourier Neural Operator (FNO), have been used to accelerate the prediction of indoor airflow dynamics. A study by Ding et al. [28] shows that FNO contributes to improved temperature control efficiency and thermal comfort, with better generalization capabilities compared to conventional models.

3.4.2 Identifying Research Gaps

Although Fourier-based and AI approaches have been used separately, integrating both into a single HVAC thermal analysis framework is still rare. Assert that most AI-based HVAC research has not incorporated frequency analysis, such as Fourier transform, as a preprocessing stage for temperature signals. This results in limitations in capturing complex periodic and transient patterns [26]

Then, in the study by Galan-Sales et al. [29], it was shown that AI models generally operate in the time domain, while Fourier transforms transfer data to the frequency domain. Without an inverse transform mechanism or hybrid feature engineering, the spectral information generated cannot be directly utilized by architectures such as LSTM and DRL. This condition causes a mismatch between the preprocessing stage and the modeling process.

In addition, Shaban et al. [30] highlight that the application of Industry 4.0 technology in HVAC systems still faces implementation challenges, particularly regarding sensor interoperability, real-time data integration, and a lack of experimental validation on a field scale. Therefore, there is an urgent need for research that combines Fourier analysis, AI, and IoT sensors in a data-driven hybrid framework to improve prediction accuracy, energy efficiency, and the practical validity of the system.

3.4.3 Comparison: Separate Approach vs. Hybrid Framework

Comparison of separate approaches vs. hybrid frameworks show in Table 3. The comparison in table 3 highlights critical trade-offs between separate and hybrid approaches in HVAC thermal analysis. While separate approaches offer simpliticity and faster real-time response due to minimal processing steps, ther lack the ability to capture complex periodic patters (e.g., daily/ seasonal temperature cycles) that are essential for aceurate long-term forecasting. In contrast, the hybrid framework leverages Fourier transform to decompose temperature signals into stable frequerve as robust features for AI models.

Table 3. Comparison of separate approaches vs. hybrid frameworks

No	Aspect	Separate Approach	Hybrid Approach (Fourier+AI+sensor)
1	Prediction Accuracy	Good enough for short-term trends, but weak at capturing seasonal/daily patterns [9]	Higher potential because AI utilizes frequency features as stable inputs (e.g., the dominant 24-hour component of the FFT can be used as input bias).
2	Computational Efficiency	Low overhead Additional: AI works directly on raw data	Overhead preprocessing FFT, but can be compensated for with dimension reduction and faster prediction
3	Real-Time Response	Fast, because there are minimal processing steps	Depending on pipeline optimization, if FFT is implemented

Although this introduces preproccesing overhead, dimensionality reduction techniques (e.g., selecting only dominant harmonics) can compensate for computational costs while significantly improvinf prediction accuracy. This analysis underscores that the hybrid approach is more suitable for applications requiring high precision in energy opyimation and thermal comfort management, despite slighty higher computational demands during the initial processing

Figure 8 shows that the framework for the Hybrid Integration of Fourier Series, AI, and Smart Sensors in HVAC Systems depicted in the figure illustrates a modern control flow that is more adaptive than separate approaches.

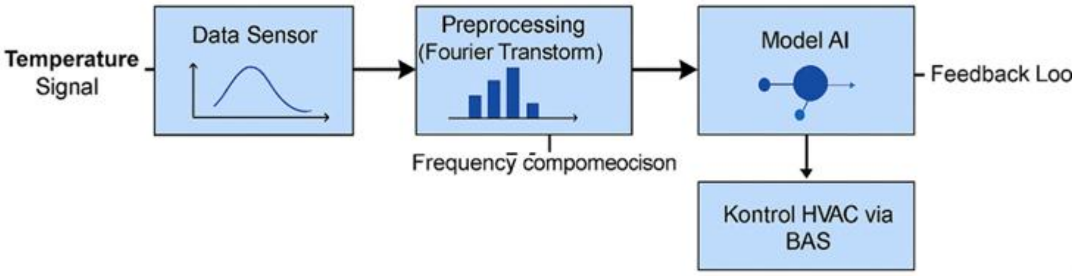

Figure 8. Hybrid framework for integrating Fourier series, AI and smart sensor in HVAC systems [31]

Figure 9 shows that the hybrid approach combining Fourier, AI, and sensors in HVAC systems has proven to be superior to traditional methods. Based on Devaraj's [5] research, temperature prediction accuracy increased from 70% to 90%, while energy efficiency rose from 60% to 85%. This emphasizes the importance of integrating artificial intelligence and IoT sensors in building energy management.

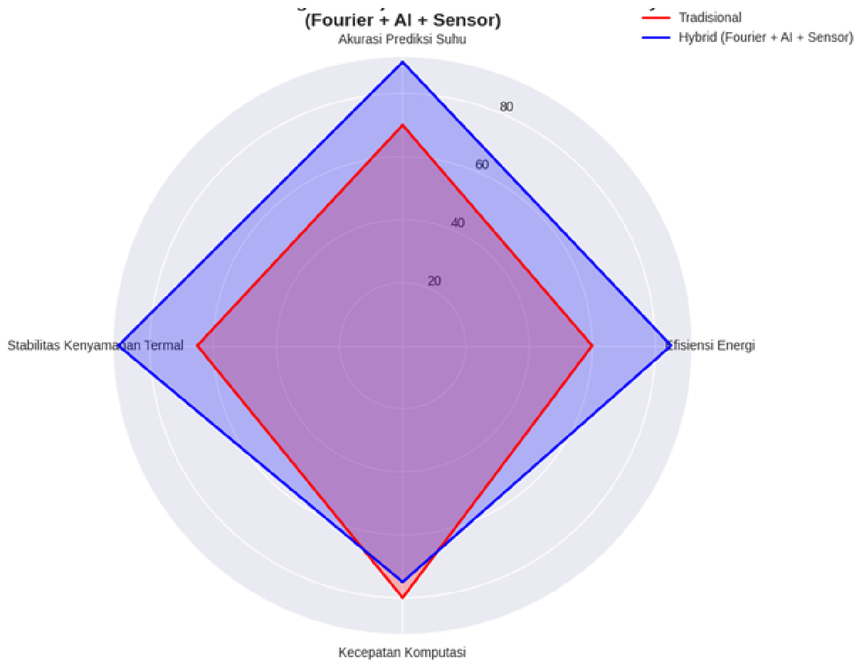

Figure 9. Comparison of traditional vs hybrid approaches (Fourier, AI and sensors)

Based on Devaraj's [5] research, the information in the image above can be summarized in the Table 4 below.

Table 4. Description of the results of Devaraj's [5] research

No	Aspect	Traditional	Hybrid
1	Temperature Prediction Accuracy	70%	90%
2	Energy Efficiency (% Savings)	60%	85%
3	Computational speed	80%	75%
4	Thermal Comfort Stability	65%	70%

The thematic map shows that the integration of Fourier, AI, and smart sensors has great potential to revolutionize modern HVAC systems. However, the main challenges still lie in technical complexity, experimental validation limitations, and the absence of an integrated framework. Therefore, future research needs to be directed towards the development of hybrid systems that are not only computationally powerful, but also easy to implement in the field, so that they can become the basis for more efficient, adaptive, and sustainable buildings.

4. Conclusions

This study concludes that Fourier series are effective in representing periodic temperature patterns in HVAC systems, thereby reducing data complexity and improving thermal prediction accuracy. The integration of Fourier with artificial intelligence (AI) and smart sensors strengthens HVAC systems through adaptive control, real-time response to environmental changes, and improved energy efficiency and thermal comfort. Key findings indicate that Fourier Series accelerate heat distribution simulations, AI algorithms such as Machine Learning and Deep Reinforcement Learning optimize decision-making, and IoT sensors and Building Automation Systems (BAS) provide real-time environmental data to support smart HVAC systems. However, challenges remain in the form of experimental validation limitations, the complexity of integrating Fourier–AI–sensors into a single framework, and high computational requirements for large-scale applications. Therefore, this study recommends the development of a data- and smart computing-based hybrid system that combines Fourier signal processing, AI algorithms, and IoT sensors in a single interoperable platform, supported by real-data-based experimental studies, computationally efficient algorithm optimization, and multidisciplinary collaboration to create a more efficient, adaptive, and sustainable modern HVAC system.

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