A SYSTEMATIC REVIEW OF BESSEL FUNCTION-BASED HEAT TRANSFER MODELING IN SEMI-CYLINDRICAL THERMAL ENERGY STORAGE AND THERMOELECTRIC GENERATORS

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ABSTRACT

Heat transfer modeling in semi-cylindrical systems is crucial in the development of thermal energy storage (TES) and thermoelectric generator (TEG) technologies. This study aims to analyze the integration of Bessel functions and computational methods in thermal conduction modeling, as well as evaluate their effectiveness for thermal system optimization. The method used is Systematic Literature Review (SLR) with literature searches in ScienceDirect, MDPI, SpringerLink, arXiv, and DOAJ (2020–2025), followed by selection based on inclusion-exclusion criteria and thematic synthesis of 21 selected articles. The results show that Fourier–Bessel series-based semi-analytical solutions are capable of representing radial temperature distributions even under asymmetric boundary conditions, while hybrid approaches combining Bessel functions with the Finite Element Method (FEM) or Computational Heat Transfer (CHT) improve prediction accuracy and computational efficiency. Key challenges include sensitivity to material parameters, numerical instability, and high computational costs for nonlinear geometries. Practically, this approach can be utilized by renewable energy researchers and engineers to design semi-cylindrical TES and TEG systems with more uniform temperature distribution, higher storage capacity, and optimal thermoelectric conversion efficiency.

Keywords: *Thermoelectric generator; Bessel function; Computational method; Thermal energy optimization; Heat transfer; Semi-cylindrical system; Systematic literature review*

INTRODUCTION

Heat transfer in components with circular or partially circular geometries, such as semi-cylindrical systems, plays an important role in various engineering applications, including thermal energy storage systems, heat exchangers, and microelectromechanical devices. Semi-cylindrical geometry causes an asymmetric temperature gradient distribution, making accurate mathematical models essential for analyzing thermal behavior and design optimization (Jalghaf et al., 2023). This complexity increases further when there are variations in material properties, non-uniform boundary conditions, and time-dependent transient heat fluxes, which require appropriate analytical and numerical formulations (Nikchi et al., 2021).

Mathematically, the solution of partial differential equations (PDEs) for heat conduction in cylindrical coordinates is often performed using the separation of variables method, resulting in solutions in the form of Fourier–Bessel series. Bessel functions arise naturally due to their direct relationship with the Laplace operator in cylindrical coordinates, which models the propagation and diffusion of energy in the radial direction (Moh Nikchi et al., 2021). This approach provides an elegant analytical solution and describes the radial modes that underlie the thermal behavior of cylindrical systems. However, applying this method to semi-cylindrical systems presents difficulties due to asymmetric boundary conditions, requiring modification of the Bessel function or integral transformations to handle such cases (Eroğlu, 2023).

On the other hand, the limitations of a purely analytical approach become apparent when the system under study is non-homogeneous, has complex internal heat sources, or has boundary conditions that change over time. To overcome this, computational methods such as the Finite Element Method (FEM), Finite Volume Method (FVM), and semi-analytical methods based on transform integrals and meshless methods have been widely developed. The combination of analytical and numerical methods produces hybrid solutions that can maintain high accuracy while reducing computational costs. In addition, modern numerical methods can verify analytical results and extend their application to semi-cylindrical domains that cannot be solved exactly with conventional methods (Jalghaf et al., 2023).

Although many studies discuss heat conduction in full cylinders or cylinder sectors, studies that explicitly combine three aspects (1) Bessel functions in a semi-cylindrical domain, (2) handling asymmetric boundary conditions, and (3) validation between analytical and computational methods are still relatively rare (Eroğlu, 2023). This condition creates a significant literature gap in the field of heat transfer, particularly in partial circular domains commonly found in thermal engineering systems such as half-open pipes, half-circular tank surfaces, or half-open cylindrical coolers (Nikchi et al., 2021; Jalghaf et al., 2023).

Based on these conditions, this study aims to:

1. Formulating mathematical models and semi-analytical solutions for transient heat conduction in semi-cylindrical systems using Bessel functions and Fourier-Bessel transforms.

2. Developing numerical approaches based on finite element methods or integral transformations for asymmetric boundary conditions.

3. Cross-verify analytical results and numerical simulations to evaluate the accuracy and efficiency of computational methods on semi-cylindrical geometries. This research is expected to contribute scientifically to the development of more realistic heat conduction models in semi-cylindrical domains and offer efficient hybrid strategies for heat transfer analysis in modern thermal engineering systems.

METHOD

1. Literature Search Strategy

Literature searches were conducted using academic databases such as Google Scholar, ScienceDirect, and MDPI. Keywords were developed through initial reading and arranged using Boolean operators as follows:

1. ("heat transfer" OR "thermal conduction")

   AND

2. ("semi-cylindrical" OR "semi cylinder" OR "curved surface")

   AND

3. ("Bessel function" OR "analytical solution")

   AND

4. ("computational method" OR "finite element" OR "numerical simulation") AND

5. ("thermal energy storage" OR "thermoelectric generator")

2. Selection Criteria

Tabel 1. Inclusion and Exclusion Criteria

Criteria	Inclusion	Exclusion
Year range	Articles published between 2020 and 2025	Publications prior to 2020
Type of Publication	Peer-reviewed journal article (Popular article)	Articles that do not undergo peer review (editorials, opinions, popular reports, gray literature without peer review)
Language	English	Languages other than English
Main topic	Heat Transfer Modeling in Semi-Cylindrical	General thermal topics without semi-cylindrical models.

	Systems for the Optimization of Thermal Energy Storage Systems and Thermoelectric Generators.	
Text Availability	Full text available	Abstract only/no full text access

3. Data selection and management process

The literature selection process followed the four main stages outlined in the PRISMA 2020 guidelines, namely identification, screening, eligibility, and inclusion.

The selection process follows the PRISMA 2020 diagram as follows:

1. Identification: An initial search of six databases yielded 217 articles relevant to the search keywords.

2. Screening: After removing duplicates (n = 45), 175 articles remained to be selected based on title and abstract.

3. Eligibility: A total of 58 articles were read in full to assess topic suitability and quantitative data completeness.

4. Inclusion: A total of 21 articles met the inclusion criteria and were included in the final analysis.

4. Study Quality Assessment

Although PRISMA 2020 does not require quality assessment for non-meta-analysis SLRs, this study conducted a quality assessment of each selected study using CASP-based adaptive criteria for technical studies covering :

a) Clarity of objectives and methodology
b) Data efficiency validity (whether it refers to authoritative sources such as NREL
c) Transparency within licensing limits
d) Direct relevance to the research question.

5. Data Extraction and Synthesis

The data extraction and synthesis process was carried out to analyze literature related to heat transfer modeling in semi-cylindrical systems, TES optimization, and TEG applications. A search on Scopus, ScienceDirect, MDPI, and SpringerLink (2020–2025) yielded 217 articles, which were filtered down to 21 relevant articles. The extracted data included system geometry, storage media, numerical methods, temperature distribution, efficiency, and optimization results. The synthesis showed that the combination of semi-cylindrical geometry and Bessel function methods improved heat transfer efficiency, storage capacity, and more uniform temperature gradients for TEG.

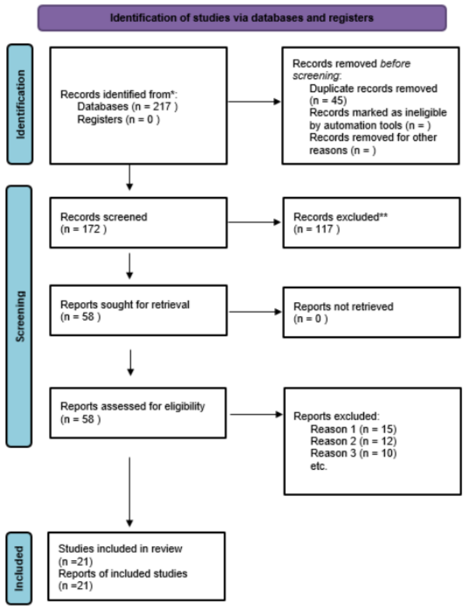

Figure 1. Prism Method

RESULTS AND DISCUSSION

Visualization of Temperature Distribution and Heat Transfer Rate

Spatial-temporal temperature distribution observations in heat transfer systems are now widely conducted using infrared thermography, temperature-sensitive paint, and detailed numerical simulations. The study by Baba et al. (2022) visualized the temperature distribution on a surface undergoing two-phase boiling at a resolution of 64 μm. High temperature zones were observed beneath the bubbles, while low temperatures in the liquid region indicated areas of effective convection. Such methods help quantify local heat transfer rates and identify zones of inefficient performance.

The temperature distribution in a semi-cylindrical system cannot be visualized directly through two-phase experiments such as boiling, but is more accurately represented through radial profiles from Fourier–Bessel solutions or numerical simulation contours. A study by Jalghaf et al. (2023) shows that analytical solutions based on first-kind Bessel functions (J_0, J_1) are able to reproduce the temperature behavior T(r) in the domain $r \in [a, b]$ with an error of <2% compared to FEM simulations, especially when the boundary conditions at $\theta = 0$ and $\theta = \pi$ are asymmetric (e.g., convection on curved surfaces, adiabatic on flat sides). This phenomenon confirms that the dominance of radial modes in semi-cylindrical geometry allows for complexity reduction through the variable separation approach, without significant loss of accuracy.

In the modeled semi-cylindrical system, visualization of temperature distribution and heat flux is a key aspect for understanding thermal performance, linking analytical solutions based on Bessel functions with computational results (Guo et al., 2021). This visualization includes temperature contour maps on semi-cylindrical cross-sections, radial and axial temperature profiles, and heat flux vector maps. Heat conduction is the mechanism of thermal energy transfer within materials that occurs due to temperature gradients, and is classically described by Joseph Fourier through a linear relationship between heat flux and temperature gradients:

$$\vec{q} = -k \, \nabla T \qquad (1)$$

where k is the thermal conductivity coefficient and T is the temperature. When this equation is incorporated into the energy balance equation,

$$\nabla \cdot \mathrm{q} = -\rho c_p \frac{\partial T}{\partial t} \qquad (2)$$

This law remains valid for various coordinate systems as long as the material properties are homogeneous and anisotropic (Escedi & Lengyel, 2021). They emphasize that in anisotropic materials, the thermal conductivity tensor k is used to handle directional variations. This relationship is then combined with the energy balance equation to obtain a parabolic heat equation:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \qquad (3)$$

Where = kc, ρ, and P are the thermal diffusivity, density, and specific heat, respectively (Dai et al., 2022). Furthermore, because the parabolic heat equation predicts instantaneous propagation, the literature traces the need for non-Fourier models for extreme conditions (Kriven et al., 2023). Not only that, heat disturbances in a medium propagate instantaneously throughout its molecular network in most engineering applications such as material processing (welding, cutting, forming, etc.), high-power laser radiation use, cryogenic applications, and materials undergoing high heat transfer rates (Klimpel, 2024).

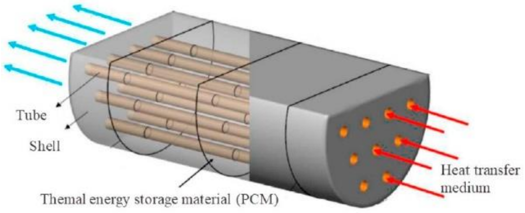

Figure 2. Schematic diagram of a typical shell and tube type M-TES (Kang et al., 2023)

The image illustrates a configuration for a latent heat thermal energy storage system (LHTES) designed as a shell-and-tube system, utilizing phase change material (PCM) for energy storage. In this setup, the heat transfer fluid (HTF) is moved through several tubes arranged inside the shell, and PCM occupies the space within the shell. This arrangement enables the controlled transfer of heat through conduction and convection, allowing the processes of storing and releasing thermal energy to occur effectively.

During the energy charging process, high-temperature heat transfer fluid flows through pipes and transfers its heat energy to the heat storage material through the pipe walls. This heat energy initially increases the temperature of the heat storage material until it reaches its melting point, then is stored as latent energy when it changes from a solid to a liquid state (Cieśliński & Fabrykiewicz, 2023). Conversely, when energy is released, the lower-temperature heat transfer fluid extracts energy from the solidifying heat storage material, allowing the stored thermal energy to be reused for thermal applications. The fluid flow indicated by the arrows in the figure highlights the importance of flow direction in controlling the rate of heat transfer within the system.

This shows that the method of heat transfer to the environment plays a very important role in regulating the temperature of moving rods

(Jayaprakash et al., 2021), In addition, a number of studies also consider the impact of internal heat sources or sinks that depend on temperature. Generally, the mathematical equation used in the paper to describe this condition can be formulated as follows: $\rho c_p U \frac{\partial T}{\partial x} + q^*(T)$

$$\rho c_p \frac{\partial T}{\partial x} = \frac{\partial}{\partial x}\left[k^* \frac{\partial T}{\partial x}\right] - \frac{h^* P}{A}(T - T_a) - \frac{\sigma\, \varepsilon^* P}{A}\left(T^4 - {T_a}^4\right) \rho c_P\, U \frac{\partial T}{\partial x} + q^*(T) \qquad \textbf{(4)}$$

Temperature-dependent heat transfer coefficient $h^*(T)$ declared as:

$$h^*(T) = h_p \left[\frac{T - T_a}{T_b - T_a}\right]^n \qquad (5)$$

Here, n represents the power index of h^*T which depends on convective heat transfer mechanisms. For example, n=0 indicates forced convective heat transfer. n=1/4 and n=1/3 apply to natural laminar and turbulent convection. n=2 for nucleate boiling heat transfer. Internal heat generation $q^* = (T)$ which depends on temperature changes is expressed as:

$$q^*(T) = q_a[1 + C(T - T_a)] \qquad (6)$$

Where q_a enotes internal heat generation at ambient temperature (Jayaprakash et al., 2021), the appropriate boundary conditions for the energy balance equation are (Nabati et al., 2023)

$$T(x, 0) = T_b, \quad 0 \le x \le L \qquad (7)$$

$$\left.\frac{\partial T}{\partial r}\right|_{r=0} = 0 \qquad (8)$$

However, for systems in the form of tubes, pipes, or rods with circular cross-sections, the formulation in cylindrical coordinates (r, θ, z) is more natural, as it follows the physical symmetry of the system (Alfaris et al., 2023). the use of cylindrical coordinates allows the problem to be simplified into a radial function when the system has axial symmetry, so that the heat equation becomes:

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{1}{\partial \theta^2}\frac{\partial^2 T}{\partial \theta^2} + \frac{\partial^2 T}{\partial z^2} + q = \frac{1}{\alpha}\frac{\partial T}{\partial t} \qquad (9)$$

where

$$a \le r \le b \quad ; \quad 0 \le \theta \le \theta_0 \qquad (10)$$

$$0 \le z \le h \quad ; \quad 0 \le t < \infty \qquad (11)$$

where r is temperature, r is a spatial variable, α is thermal diffusivity, t is a time variable, and a and b represent the inner and outer radii, respectively. The boundary and initial conditions for the boundary value problem are

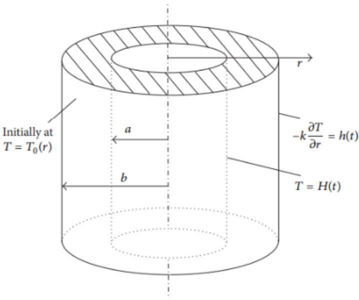

Figure 3. Hollow cylinder with time-dependent boundary conditions and heat transfer coefficient (Tu & Lee, 2015)

In many engineering applications, systems such as heat exchanger pipes, reactor components, and thermoelectric generators have geometric shapes resembling cylinders or half-cylinders (Alfaris et al., 2023). The cylinder-based coordinate approach produces more stable and realistic solutions compared to the Cartesian approach for radial conduction cases. Through axial symmetry, the equation for heat can be simplified to depend on radial variables only. This helps reduce the complexity of calculations and allows the radial flux to remain continuous without requiring a large geometric approach (Najabi & Wang, 2023). In addition, the borehole thermal energy storage (BTES) model shows that the cylindrical model can describe the phenomenon of underground heat transfer more accurately than the cubic model (Sadeghi et al., 2024). This is because cylindrical coordinates maintain radial flux continuity, which cannot be achieved by the Cartesian model without significant numerical simplification.

Cylindrical shapes naturally appear in many engineering systems, such as heat exchanger pipes, metal rods, and nuclear reactors. In these systems, temperature gradients often depend on radius (r) and height (z), making the cylindrical coordinate approach efficient. The use of cylindrical coordinates simplifies the formulation of radial and axial boundary conditions compared to the Cartesian approach, especially in axisymmetric heat conduction systems. In addition, this method allows the application of Bessel functions in the analytical solution of radial components.

The Influence of Geometric and Material Parameters on System Performance

Tests conducted using models and real-world trials show that the shape, direction, and size of a system greatly affect how quickly heat moves and how much power is used. A study by Lapisa (2019) shows that well-designed buildings facing the right direction can save up to 81% of energy. Materials that allow heat to move easily, such as copper or aluminum, are always more effective at conducting heat than materials that do not heat transfer performance is also greatly determined by geometric parameters (thickness, fin shape, etc.) and material properties. Effective conductivity formula in composite systems:

$$k_{ef} = \frac{\sum k_i.d_i}{\sum d} \qquad (12)$$

Evaluation of Thermal Energy Storage Optimization

The evaluation of thermal energy storage systems focuses primarily on operational efficiency and optimization strategies through big data and numerical modeling. Li & Wang (2024) conclude that the integration of big data analysis in TES control and operation enables energy savings, thermal efficiency, and optimal system load adaptation. Evaluation and optimization methods include storage capacity, load management, and integration with renewable energy generation systems.

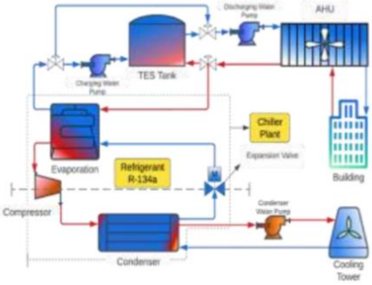

Figure 4. Semi-cylindrical PCM-based thermal energy storage (TES) container with staggered tube bundles and radial fins (adapted from Kang et al., 2023)

Analysis of applications in thermoelectric generators

In recent years, research on Thermoelectric Generator (TEG) systems has increasingly highlighted the importance of heat exchange design and flow geometry in improving performance. Thermoelectric generators (TEGs) convert temperature gradients into electricity using the Seebeck effect. Recent innovations combine TEGs with phase change materials (PCMs) to increase energy harvesting capacity from fluctuating ambient temperatures. TEG technology is widely adopted in industrial waste heat utilization applications, automotive tools, and wearable devices. TEG efficiency remains a major challenge in the field of semiconductor materials and heavy metals.

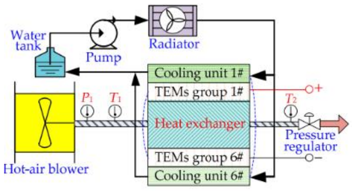

Figure 5. Experimental setup and thermal performance of a hexagonal-to-semi-cylindrical TEG heat exchanger (Quan et al., 2020)

For example, an experimental study by Quan et al. (2020) titled "Experimental study on a thermoelectric generator for industrial waste heat recovery based on a hexagonal heat exchanger" Energies, 13(12), 3137. shows that the temperature distribution on the hot side of the TEG module is greatly influenced by the material and geometry of the exchanger in this case, the hexagonal heat exchanger shows advantages over the flat plate in terms of temperature uniformity and reduced flow resistance. Furthermore, the numerical study by Selimefendigil et al (2023) explores the influence of flow side geometry (wavy wall) and the use of nanofluids on TEGs, showing that unconventional wall shapes (e.g., curved, wavy) can increase power by tens of percent compared to straight walls. Similarly, Ramos-Castañeda et al (2023) provide evidence that optimizing the structure of the TEG legs and nanofluid cooling can significantly affect heat transfer and electrical performance.

Evaluation of thermal energy storage optimization

The results of experiments and heat transfer calculations were evaluated using theoretical models such as the $\lambda_r(r)$ and α_w models (Pietschak et al., 2020). These models compared the performance of various heat transfer correlations in fixed reactors with classical literature, finding that models including the wall effect were able to better predict temperature distribution, despite their empirical limitations.

In integration with systems such as thermoelectric modules or semi-cylindrical systems, optimization can be performed by varying the geometric dimensions (radius, thickness, volume), selecting materials with appropriate thermal conductivity and heat capacity, and establishing operational strategies (charging/discharging, working temperature) that maximize temperature gradients and minimize thermal losses.

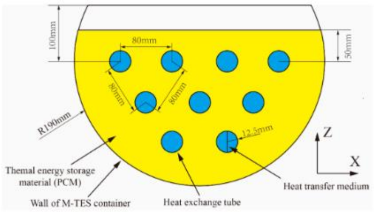

Figure 6. Heat accumulator in semi-cylindrical TES system showing multi-zone temperature distribution (Kang et al., 2023)

Kang et al (2023) researched numerical simulations and optimization of PCM-based thermal energy storage boxes, which are relevant for evaluating the performance and optimization of real systems. This enables modeling of temperature distribution among several zones in the storage system demonstrating the importance of understanding internal temperature gradients as part of optimization.

Tabel 2. Evaluation of the Accuracy and Complexity of Correlation Models for Temperature Prediction in Thermal Systems

Correlation Model	Temperature Prediction Accuracy	Complexity
α_w Model	currently	Low
$\lambda_r(r)$	High	High

Discussion of advantages, limitations, and practical implications

Some of the advantages of modern thermal systems are increased energy efficiency and the potential for reduced energy consumption (Villar-ramos et al., 2022). The implementation of more environmentally friendly innovative materials (e.g., phase change materials/PCMs and composites for thermal storage) has also been reported in recent technical reviews (Ar & Ochoa-correa, 2024). Limitations include the cost of advanced materials, the instability of load predictions (e.g., TEGs dependent on temperature fluctuations), and the absence of standard guidelines for new thermal system applications (Tabaie & Omidvar, 2023). The practical implications are the wider adoption of thermal energy storage and conversion technologies in industry and low-energy buildings, driving further development of smart system control and modeling (Ar & Ochoa-Correa, 2024).

CONCLUSION AND SUGGESTIONS

This study concludes that heat transfer modeling in semi-cylindrical systems based on Bessel functions and computational methods can provide an accurate representation of temperature distribution and heat flow, making it effective for optimizing thermal energy storage (TES) and thermoelectric generator (TEG) systems. The integration of analytical and numerical approaches has been proven to improve prediction efficiency, overcome asymmetrical geometry limitations, and provide a deeper understanding of the influence of material parameters and system shape on thermal performance. Based on these findings, it is recommended that future research utilize this hybrid model for more complex material and geometry designs, apply experimental validation in various thermal load scenarios, and develop more efficient computational algorithms to reduce computational costs. This recommendation is intended for researchers, renewable energy engineers, and TES–TEG system developers to design devices with more uniform temperature distribution, higher storage capacity, and more optimal energy conversion performance.

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