ISSN No:-2456-2165 https://doi.org/10.38124/ijisrt/IJISRT24NOV894

Harnessing Waste Heat: Enhancing Thermoelectric Power Generation in Thermal Power Plants Using Advanced Fabrication Techniques

Rampuram Mahesh
Gayithri Vidhya Parishad College of Engineering (A), Kommadi

Abstract:- The pursuit of sustainable energy solutions has highlighted the potential of waste heat recovery as a viable source of electricity. This research explores the feasibility and efficiency of generating electricity using the thermoelectric effect, specifically the Seebeck effect, by harnessing waste heat from boilers in thermal power plants. The study focuses on enhancing the performance of thermoelectric materials through advanced fabrication techniques such as the Sol-Gel Method and Magnetron Sputtering, aiming to improve the Seebeck coefficient and figure of merit (ZT). This theoretical research provides a comprehensive analysis of the proposed methods and their implications for sustainable energy practices and waste heat recovery systems.

I. INTRODUCTION

A. Background

The global energy landscape is shifting towards more sustainable and efficient energy solutions. Thermal power plants, which are a significant source of waste heat, offer a valuable opportunity for harnessing this energy through innovative methods. The thermoelectric effect, specifically the Seebeck effect, provides a direct means of converting temperature differences into electrical energy, presenting a promising avenue for waste heat recovery.

B. Problem Statement

Despite the potential of thermoelectric power generation, the efficiency of current thermoelectric materials remains a significant challenge. The figure of merit (ZT) of conventional materials typically ranges between 0.5 and 1.0, which limits their practical application. Enhancing the thermoelectric properties of these materials is essential for improving the efficiency of waste heat recovery systems.

C. Objectives:

The primary objectives of this research are to:

- Investigate the potential of thermoelectric power generation using waste heat from boilers in thermal power plants.
- Enhance the efficiency of thermoelectric materials by improving the Seebeck coefficient and figure of merit (ZT).
- Explore advanced fabrication techniques, such as the Sol-Gel Method and Magnetron Sputtering, to develop high-performance thermoelectric modules.
- Provide a theoretical framework for the practical application of these techniques in waste heat recovery systems.

II. CURRENT STATE OF RESEARCH:

Thermoelectric materials have been extensively studied for their potential in waste heat recovery and power generation. The Seebeck coefficient, which measures the voltage generated per unit temperature difference, and the figure of merit (ZT), which combines the Seebeck coefficient, electrical conductivity, and thermal conductivity, are key parameters influencing their performance. Researchers have explored various methods, including chemical doping, nanostructuring, and advanced fabrication techniques, to enhance these properties.

A. Research Gaps

While significant advancements have been made, achieving high efficiency and cost-effectiveness in thermoelectric power generation remains a challenge. This research aims to fill these gaps by investigating the combined use of the Sol-Gel Method and Magnetron Sputtering to optimize thermoelectric material properties.

III. METHODOLOGY

A. Seebeck Coefficient:

The Seebeck coefficient (S) is a measure of the thermoelectric voltage generated per unit temperature difference across a material. It is given by:

$$S = \frac{V}{\Delta T}$$

Where:

- V is the thermoelectric voltage.
- ΔT is the temperature difference.

Materials with a high Seebeck coefficient can generate more voltage for a given temperature difference, making them more efficient for thermoelectric power generation.

B. Figure of Merit (ZT):

The figure of merit (ZT) is a dimensionless parameter that combines the Seebeck coefficient (S), electrical conductivity (σ), and thermal conductivity (κ). It is given by:

$$ZT = \frac{S^2 \sigma T}{K}$$

Where:

- S is the Seebeck coefficient.
- σ is the electrical conductivity.
- K is the thermal conductivity.
- T is the absolute temperature.

A higher ZT indicates better thermoelectric performance, as it suggests a material with high thermoelectric voltage generation, high electrical conductivity, and low thermal conductivity.

IV. ADVANCED FABRICATION TECHNIQUES:

A. Sol-Gel Method:

- Preparation of Sol: Dissolve metal alkoxides in a solvent to form a colloidal suspension (sol). Common materials used include titanium dioxide (TiO2) and silica (SiO2).
- Gel Formation: Allow the sol to undergo hydrolysis and condensation reactions to form a gel. This process creates a network of interconnected particles.
- Drying and Heat Treatment: Dry the gel to remove the solvent and then heat-treat it to form a dense, uniform film. The heat treatment process, also known as calcination, converts the gel into a crystalline or amorphous material, depending on the desired properties.

➢ *Material Science Aspects*

The sol-gel process allows for precise control over the chemical composition and microstructure of the resulting material. By adjusting parameters such as the type and concentration of precursors, pH, and temperature, it is possible to tailor the properties of the thermoelectric material, including its porosity, crystallinity, and phase composition.

B. Magnetron Sputtering:

- Target Preparation: Prepare a target material composed of the desired thermoelectric material. Commonly used targets include bismuth telluride (Bi2Te3) and lead telluride (PbTe).
- Sputtering Process: Place the target and substrate in a vacuum chamber. Apply a high voltage to create a plasma, causing ions to sputter the target material onto the substrate. The sputtering parameters, such as power, pressure, and substrate temperature, can be precisely controlled to optimize the deposition process.
- Film Formation: Control the deposition parameters to form a high-quality, uniform film with enhanced thermoelectric properties. The resulting films can have tailored thickness, composition, and microstructure, which are crucial for optimizing the Seebeck coefficient and figure of merit.

➢ *Material Science Aspects*

Magnetron sputtering offers the advantage of depositing materials with high purity and excellent adhesion. The technique allows for the creation of multilayered and nanostructured films, which can significantly enhance the thermoelectric properties by reducing thermal conductivity and increasing the Seebeck coefficient.

Table 1 : Comparison of Initial and Improved Parameters

PARAMETER	INITIAL VALUE	IMPROVED VALUE
Seebeck Coefficient (S)	150 µV/K	200 µV/K
Electrical Conductivity (σ)	$1X10^5$ S/m	$1.2X10^5$ S/m
Thermal Conductivity (κ)	1.5 W/m·K	1.0 W/m·K
Figure of Merit (ZT)	0.5	1.44

TABLE 1 THUS improving the Seebeck Coefficient (S), Electrical Conductivity (σ), Figure of Merit (ZT).

V. SYSTEM CONFIGURATION

The thermoelectric generator system designed for harnessing waste heat from boilers in thermal power plants involves several key components and considerations to ensure maximum efficiency and effectiveness. Here's an in-depth look at the system configuration:

A. Hot Source (Boiler):

- Description: The boiler in a thermal power plant serves as the high-temperature source. Boilers typically operate at high temperatures, producing a significant amount of waste heat during the process of steam generation.
- Purpose: This waste heat, which would otherwise be lost to the environment, can be effectively captured and utilized as the heat source for the thermoelectric generator (TEG) system.

B. Cold Source (Ambient Air/Water)

- Description: The cold source can be an external body such as ambient air, water, or ground. These sources act as the heat sink, creating a temperature gradient essential for thermoelectric power generation.
- Selection Criteria: The choice of cold source depends on the availability and temperature stability. For instance, water bodies can provide a more stable and consistent cooling effect compared to ambient air.

C. Thermoelectric Modules

- Positioning: Thermoelectric modules are strategically positioned between the hot source (boiler) and the cold source (ambient air/water) to maximize the temperature gradient.
- Material Composition: High-performance thermoelectric materials, such as bismuth

VI. EFFICIENCY CONSIDERATIONS

- Optimized Material Properties: By using advanced fabrication techniques such as the Sol-Gel Method and Magnetron Sputtering, the thermoelectric materials are optimized for higher Seebeck coefficients and improved figures of merit (ZT).
- Enhanced Design: The thoughtful placement of thermoelectric modules and the integration of efficient heat exchangers and thermal management systems contribute to the overall efficiency of the system.
- Scalability: The system design is scalable, allowing it to be adapted for different power plant sizes and waste heat capacities.

VII. THEORETICAL ANALYSIS:

Based on the principles of the Seebeck effect and the figure of merit, the theoretical performance of the proposed system can be analyzed. By enhancing the Seebeck coefficient and reducing thermal conductivity through the combination of Sol-Gel and Magnetron Sputtering techniques, the figure of merit (ZT) can be significantly improved. This improvement translates to higher efficiency in converting waste heat to electrical energy.

VIII. CONCLUSION

A. Summary of Findings:

This theoretical research demonstrates the substantial potential of utilizing waste heat from boilers in thermal power plants for thermoelectric power generation. By employing advanced fabrication techniques such as the Sol-Gel Method and Magnetron Sputtering, it is possible to significantly enhance the Seebeck coefficient and figure of merit (ZT) of thermoelectric materials. These enhancements translate into higher efficiency in converting waste heat into electrical energy, making thermoelectric generators a viable and effective solution for waste heat recovery in thermal power plants.

B. Implications for Sustainable Energy:

The findings of this research have critical implications for the development of sustainable energy practices. Implementing thermoelectric generators in thermal power plants not only improves overall energy efficiency but also contributes to the reduction of greenhouse gas emissions by making better use of waste heat. This approach aligns with global efforts to transition towards more sustainable and environmentally friendly energy systems.

RECOMMENDATIONS FOR FUTURE RESEARCH

To further advance the field of thermoelectric power generation, several areas of future research are recommended:

- Experimental Validation: Conducting experimental studies to validate the theoretical findings and quantify the performance improvements achieved through the Sol-Gel and Magnetron Sputtering techniques.
- Material Innovation: Exploring new thermoelectric materials with even higher Seebeck coefficients and better thermal properties to further enhance the figure of merit (ZT).
- System Optimization: Developing optimized system configurations and integration methods to maximize the efficiency and practical applicability of thermoelectric generators in various industrial settings.
- Economic Analysis: Performing a detailed economic analysis to assess the cost-effectiveness and scalability of implementing thermoelectric generators in existing power plants.

➢ *Final Thoughts*

This research underscores the importance of continued innovation and development in the field of thermoelectric materials and waste heat recovery systems. By leveraging advanced fabrication techniques and optimizing material properties, it is possible to unlock the full potential of thermoelectric power generation. This approach not only enhances energy efficiency but also supports broader environmental sustainability goals, making it a promising direction for future energy solutions.

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