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2025
PhD THESIS
MECHANICAL ENGINEERING

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Department of Mechanical engineering
Prepared as
PhD Thesis

KARABÜK
November 2025

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ABSTRACT

PhD Thesis

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Karabük University
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The Department of Mechanical Engineering

Thesis Advisor:
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Nowadays, rapid consumption of fossil fuels and increasing electricity requirement have attracted attention on renewable energy resources. Today, thermoelectric (TE) power generation has become a promising technology in energy saving and reduction of environmental impacts in the world. Thermoelectric generators (TEGs), based on Seebeck effect, are used in power generation by recovering waste heat released from automobiles, factories, and similar resources.

In this study, high temperature thermoelectric generators with 8 pairs of rectangular prism (TEG_{RP}) and cylindrical legs (TEG_C) were fabricated individually and experimentally investigated. Within this scope, oxide thermoelectric materials of dually doped $Ca_{2.5}Ag_{0.3}Eu_{0.2}Co_4O_9$ and $Zn_{0.96}Al_{0.02}Ga_{0.02}O$ with the highest figure of merit (zT) values of 0.57 and 0.17 were selected among 19 different compositions. TE powders were synthesized using sol-gel method following cold pressing for consolidation of $n-$ and $p-$type legs of both TEGs. Prior to the fabrication of the TEGs, geometrical optimization of the legs was performed for both TEGs using Response Surface Methodology and dimensions of the legs were specified.

Power generation characteristics of the TEGs were evaluated by establishing a measurement system and $I - V$ and $I - P$ curves were obtained. According to the results, open circuit voltage (V_{OC}) and maximum generated output power (P_{max}) of both TEGs increased with increasing ΔT. Maximum V_{OC} of TEG_{RP} and TEG_{C} were obtained as 133.1 mV and 158.2 mV, respectively, for the temperature difference (ΔT) of 440 °C at 495 °C hot side temperature (T_H). As the current increased, output power was generated with respect to $P \propto I^2$. P_{max} for TEG_{RP} and TEG_{C} were obtained as 33.7 mW and 45.5 mW at the same conditions.

Steady-state thermal and thermal-electric analyses were performed to evaluate power generation performances and temperature distributions of TEG_{RP} and TEG_{C}. V_{OC} and P_{max} of both TEGs increased with increasing ΔT as well as in the experimental results. Maximum V_{OC} for both TEGs were obtained as 1117 mV for 410 °C ΔT and 495 °C T_H. $I - P$ curves for both TEGs exhibited similar characteristics with the experimental results. As a result, P_{max} for TEG_{RP} and TEG_{C} were obtained as 3315.1 mW and 2632.9 mW in the same conditions. When the results of thermal-electric analyses are compared to the experimental results of fabricated TEGs, measured open circuit voltages and generated output powers were much lower than the results of thermal-electric analyses. In this study, noteworthy voltage and output power losses were correlated to the contact resistances between the TE legs and the silver conductors.

Key Words **:** Thermoelectrics, oxide materials, material characterization, thermoelectric properties, thermoelectric generator, response surface optimization, thermal-electric analysis, power generation.

Science Code **:** 914.1.233

ÖZET

Doktora Tezi

TEZ BAŞLIĞINIZIN TÜRKÇE ÇEVİRİSİNİ TÜM HARFLER BÜYÜK OLARAK BURAYA YAZINIZ

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Karabük Üniversitesi
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Kasım 2025, 131 sayfa

Günümüzde fosil yakıtların hızla tüketilmesi ve elektriğe olan artış, dikkatleri yenilenebilir enerji kaynakları üzerine çekmektedir. Bugün termoelektrik (TE) güç üretimi, enerji tasarrufu ve dünyadaki çevresel etkilerin azaltılması noktasında umut verici bir teknoloji haline gelmiştir. Temeli Seebeck etkisi olan termoelektrik jeneratörler, otomobiller, fabrikalar ve benzer kaynaklardan atılan atık ısının geri kazanılması ile güç üretiminde kullanılmaktadır.

Bu çalışmada, her biri 8 çift dikdörtgenler prizması (TEG_{RP}) ve silindirik (TEG_{C}) ayaklardan oluşan ve yüksek sıcaklıkta çalışan termoelektrik jeneratörler üretilmiş ve deneysel olarak incelenmiştir. Bu kapsamda, 19 farklı kompozisyon arasından, sırasıyla değerleri 0.57 ve 0.17 olan ve en yüksek termoelektrik verime (zT) sahip $Ca_{2.5}Ag_{0.3}Eu_{0.2}Co_4O_9$ ve $Zn_{0.96}Al_{0.02}Ga_{0.02}O$ oksit TE malzemeler seçilmiştir. TE tozlar sol-jel metodu ile sentezlenmiş, $p-$ ve $n-$tipi ayakların konsolidasyonu için soğuk presleme yöntemi kullanılmıştır. Termoelektrik jeneratörler üretilmeden önce

Tepki Yüzeyi Metodolojisi ile her iki jeneratör için jeneratör ayaklarının geometrik optimizasyonu gerçekleştirilmiş ve ayak boyutları belirlenmiştir.

Termoelektrik jeneratörlerin güç üretim karakterizasyonu için bir ölçüm sistemi kurularak $I-V$ ve $I-P$ eğrileri elde edilmiştir. Sonuçlar incelendiğinde açık devre voltajı (V_{OC}) ve maksimum çıkış gücü (P_{max}), sıcaklık farkı (ΔT) arttıkça her iki jeneratör için de artmıştır. $\mathrm{TEG_{RP}}$ ve $\mathrm{TEG_{C}}$ için maksimum V_{OC}, 440 °C sıcaklık farkı ve 495 °C sıcak yüzey sıcaklığı için sırasıyla 133.1 mV ve 158.2 mV olarak elde edilmiştir. Akım arttıkça çıkış gücü de $P \propto I^2$ orantısına bağlı olarak üretilmiştir. Aynı sıcaklık şartlarında $\mathrm{TEG_{RP}}$ ve $\mathrm{TEG_{C}}$ için P_{max}, sırasıyla 33.7 mW ve 45.5 mW olarak elde edilmiştir.

$\mathrm{TEG_{RP}}$ ve $\mathrm{TEG_{C}}$'nin güç üretim performanslarının ve sıcaklık dağılımlarının belirlenebilmesi için kararlı hal ısıl ve ısıl-elektrik analizler gerçekleştirilmiştir. Deneysel sonuçlarda olduğu gibi ΔT arttıkça V_{OC} ve P_{max} her iki jeneratör için de artmıştır. Her iki jeneratör için de maksimum V_{OC}, 410 °C sıcaklık farkı ve 495 °C sıcak yüzey sıcaklığı için 1117 mV olarak belirlenmiştir. $I-P$ eğrileri her iki jeneratör için de deneysel sonuçlar ile benzer karakteristik göstermiştir. Sonuç olarak, aynı sıcaklık şartlarında $\mathrm{TEG_{RP}}$ ve $\mathrm{TEG_{C}}$ için P_{max} sırasıyla 3315.1 mW ve 2632.9 mW olarak elde edilmiştir. Isıl-elektrik analizlerin sonuçları üretilen jeneratörlerin deneysel sonuçları ile karşılaştırıldığında ölçülen açık devre voltajı ve çıkış güçlerinin ısıl-elektrik analizleri sonuçlarının çok daha altında olduğu belirlenmiştir. Çalışmadaki bu kayda değer voltaj ve çıkış gücü kayıplarının TE ayaklar ile gümüş iletkenler arasındaki temas dirençlerinden kaynaklandığı düşünülmektedir.

Anahtar Kelimeler : Termoelektrik, oksit malzemeler, malzeme karakterizasyonu, termoelektrik özellikler, termoelektrik jeneratör, tepki yüzeyi optimizasyonu, termal-elektrik analiz, güç üretimi.

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I would like to present my foremost thanks to . . .

I appreciate to . . .

My intense gratefulness goes to . . .

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SYMBOLS AND ABBREVIATIONS INDEX

SYMBOLS

zT : Figure of merit

PF : Power factor

S : Seebeck coefficient

ρ : Electrical resistivity

ρ_n : Electrical resistivity of n-type legs

ρ_p : Electrical resistivity of p-type legs

σ : Electrical conductivity

ΔT : Temperature difference

κ : Thermal conductivity

κ_E : Electron thermal conductivity

κ_L : Lattice thermal conductivity

κ_{PH} : Phonon thermal conductivity

T_H : Hot side temperature of thermoelectric generator

T_C : Cold side temperature of thermoelectric generator

P : Generated output power

$P_{\max}$: Maximum generated output power

V : Electrical potential

V_{OC} : Open circuit voltage

I : Electric current

J : Current density

E : Electric field intensity

B : Magnetic field

R : Electrical resistance

R_{in} : Internal combined electrical resistance

l : Distance between contacts

N : Number of thermoelectric legs

V_H : Hall voltage

R_H : Hall coefficient

k_B : Boltzmann constant

h : Planck's constant

e : Electron charge

m^* : Effective mass of charge carrier

n : Carrier concentration

E_F : Fermi energy

L : Lorenz number

μ : Electron mobility

π : Peltier coefficient

β : Thomson coefficient

q : Heat flux

Q : Heat flow

α : Thermal diffusivity

ρ : Density

c_p : Specific heat capacity

c_v : Specific heat capacity of solids

R : Gas constant

$\frac{dt}{dx}$: Temperature gradient

N : Number of atoms

M : Molar mass

A : Cross-sectional area

L : Length or leg height

d : Sample thickness

y : Response variable yield

ζ_1 : Reaction time

ζ_2 : Reaction temperature

λ : Wavelength

D : Average crystalline size

β : Full width at half maximum intensity

θ : Bragg's diffraction angle

α : Thermal expansion coefficient

C : Specific heat capacity

$\dot{q}$: Heat generation rate

D : Electric flux density

Π : Peltier coefficient

∇T : Temperature gradient

T_s : Surface temperature

h : Convection heat transfer coefficient

T_∞ : Temperature of the medium

ABBREVIATIONS

TE : Thermoelectric

TEG : Thermoelectric Generator

FEM : Finite Element Method

FVM : Finite Volume Method

HIP : Hot Isostatic Pressing

CIP : Cold Isostatic Pressing

HP : Hot Pressing

CP : Cold Pressing

SPS : Spark Plasma Sintering

DTA-TG : Differential Thermal Analysis–Thermogravimetry

XRD : X-ray Diffraction

XPS : X-ray Photoelectron Spectroscopy

SEM : Scanning Electron Microscopy

TEG_{RP} : Thermoelectric generator with rectangular prism legs

TEG_{C} : Thermoelectric generator with cylindrical legs

DSC : Differential Scanning Calorimetry

DOE : Design of Experiments

RSM : Response Surface Methodology

BE : Binding Energy

FWHM : Full Width at Half Maximum Intensity

PART 1

INTRODUCTION

1.1. THIS IS A FIRST LEVEL HEADING

Recent advances in nanoscale transport have been summarized by [1], who provided a detailed theoretical framework for phonon drag effects.

For further background on non-linear oscillations, see the discussion by Jones [2].

Experimental validation of metamaterial cloaking at microwave frequencies was reported by [3].

Monte Carlo studies of lattice gauge models at finite temperature were explored by [4].

Nguyen's doctoral work [5] established a correlation between lattice strain and superconducting transition temperature.

The velocity field data used for model verification were retrieved from the Dryad repository [6].

Neural-network modeling was implemented using the open-source TensorFlow library [7].

A concise overview of the fundamental postulates can be found on Wikipedia [8].

Environmental compliance in laboratory procedures followed ISO 14001:2015 [9].

A broad philosophical overview of foundational issues is collected in an Oxford handbook [10].

For a focused chapter inside a book, see Penrose's discussion of spinors [11].

Deep residual networks were introduced at [12].

The full ICML 2020 volume is available as an edited proceedings from PMLR [13].

Shannon's master's thesis established the algebraic basis of switching circuits [14].

Turing's Princeton dissertation laid groundwork for ordinal logics [15].

Strain data for GW150914 can be obtained from LOSC [16].

Many numerical examples here were produced with NumPy [17].

Physical constants are retrieved from NIST's online database [18].

Time formatting follows the ISO date/time standard [19].

1.1.1. This is a second level heading

Classical mechanics describes the motion of a particle of mass m under a force $\mathbf{F}$ through Newton's second law:

$$\mathbf{F} = m\mathbf{a}. \tag{1.1}$$

Equation (1.1) remains a cornerstone of physics [20].

For waves on a string, the standard one-dimensional wave equation is

$$\frac{\partial^2 y}{\partial t^2} = v^2 \frac{\partial^2 y}{\partial x^2}, \tag{1.2}$$

where $v = \sqrt{T/\mu}$ is the wave speed determined by tension T and linear density μ [21].

In quantum mechanics, the time-independent Schrödinger equation reads

$$-\frac{\hbar^2}{2m}\nabla^2\psi + V\psi = E\psi, \tag{1.3}$$

first introduced by Schrödinger in 1926 [22].

1.2. FIGURE EXAMPLES

Scientific documents often include figures to illustrate results, experimental setups, or conceptual frameworks. Figure 1.1 shows a single image with a caption. The convention for captions and references follows guidelines in [23].

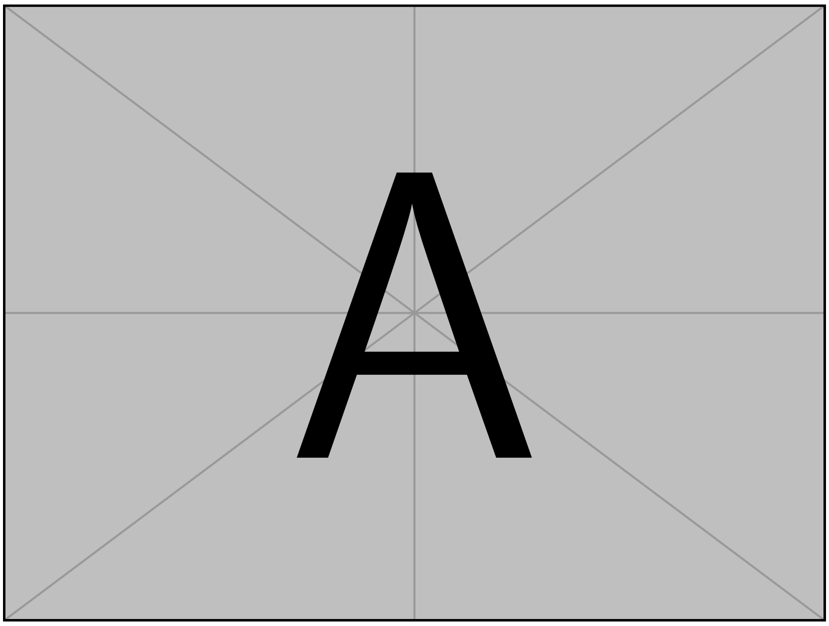
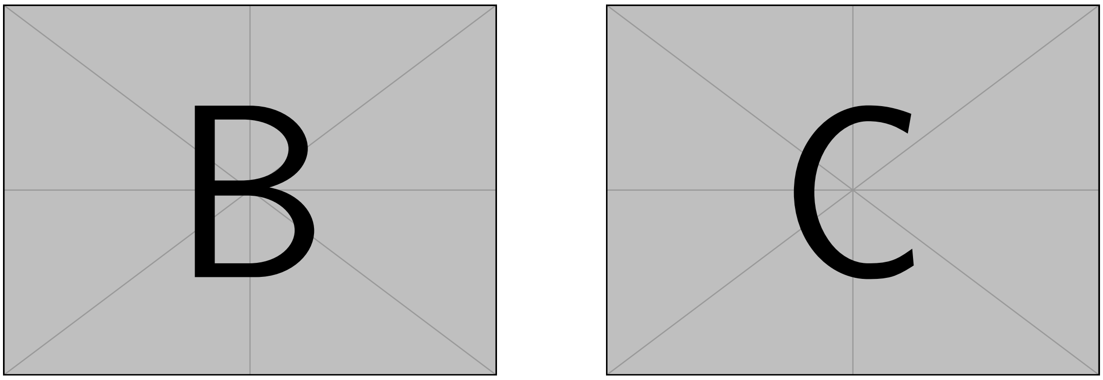


Figure 1.1. A single placeholder example image.

Multiple related panels can be combined as subfigures (Fig. 1.2); see general practices for composite figures in [24].



(a) First subfigure. (b) Second subfigure.

Figure 1.2. Example of two related subfigures side by side.

Larger works often combine multiple figures in a sequence to show progressive results (Fig. 1.3), following presentation techniques from [25].

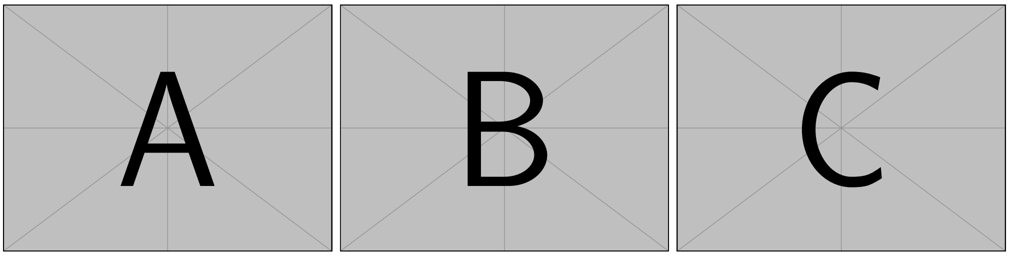


Figure 1.3. A sequence of related figures illustrating progressive results.

Finally, figures may also appear in floating environments with wide layouts such as a two-column article (not shown here), or may include multiple panels referenced collectively (e.g., Figs. 1.1–1.3).

1.3. TABLE EXAMPLES

Experimental data often appear in tabular form. Table 1.1 lists selected fundamental constants recommended by CODATA [26]. These values are widely used in numerical simulations and physical calculations.

Table 1.2 shows sample material properties adapted from standard references on solid-state materials [27]. Such data are frequently used to compare thermal and mechanical performance.

Table 1.1. Selected fundamental physical constants (CODATA 2018) [26].

Quantity	**Symbol**	**Value**
Speed of light	c	2.9979×10^{8} m/s
Planck constant	h	6.6261×10^{-34} J·s
Elementary charge	e	1.6022×10^{-19} C
Boltzmann constant	k_{B}	1.3806×10^{-23} J/K

Table 1.2. Typical properties of selected engineering materials [27].

Material	**Density (g/cm^3)**	**Elastic Modulus (GPa)**	**Thermal Conductivity (W/m·K)**
Aluminum	2.70	69	237
Copper	8.96	110	401
Steel (AISI 1020)	7.87	200	51
Silicon	2.33	130	149

In social-science or management contexts, smaller textual tables are also common. Table 1.3 illustrates a Likert-scale example as used in survey analysis [28].

Table 1.3. Example of a Likert-scale question and responses [28].

Statement	**SD**	**D**	**N**	**A**	**SA**
Physics is enjoyable	3	8	15	20	4
Mathematics is easy	5	10	12	18	5

Table 1.3 uses the abbreviations: SD (Strongly Disagree), D (Disagree), N (Neutral), A (Agree), SA (Strongly Agree).

1.4. SECTIONING AND CROSS-REFERENCING

This section demonstrates how to create hierarchical headings and cross-references. Always assign each major part of your thesis a logical structure:

- `\section{...}`
- `\subsection{...}`
- `\subsubsection{...}`

For example, the methodology details are explained in Section 1.4.1, while the results are summarized in Section 1.4.2.

1.4.1. Methodology Example

The study followed a two-stage process: simulation and verification. The simulation parameters are listed in Table 1 (not shown here). Cross-referencing is done using commands like `\ref{sec:results}`.

1.4.2. Results Example

This subsection provides the findings, which are discussed further in Section 1.5.

1.4.2.1. Statistical Analysis

Descriptive and inferential statistics were used to interpret data.

1.5. DISCUSSION

Section 1.4 described the use of sections and labels; here we connect those references logically in the narrative.

1.6. LISTS

Lists help organize information clearly. LaTeX supports both numbered and bulleted lists, as shown below.

1.6.1. Numbered List (Enumerate)

Use numbered lists for procedural steps:

1. Review existing literature.
2. Define the problem statement.
3. Design and conduct experiments.
4. Analyze data and interpret results.
5. Draw conclusions and propose future work.

1.6.2. Bulleted List (Itemize)

Use bulleted lists for unordered information:

- Experimental setup
- Numerical model
- Analytical solution

You can also nest lists if necessary:

- Input parameters:
  1. Temperature
  2. Pressure

3. Volume

- Output:

1. Energy

2. Entropy

1.7. INLINE MATHEMATICS

Mathematics can appear either inline or displayed separately. Inline math is enclosed within dollar signs `$...$`, and it flows naturally with the text.

For example, the relationship between distance d, velocity v, and time t is expressed as $d = vt$. Similarly, the kinetic energy is given by $E_k = \frac{1}{2}mv^2$, and the potential energy by $E_p = mgh$.

For larger expressions, use display mode:

$$E = \sqrt{(pc)^2 + (m_0c^2)^2}$$

Equation numbering can also be added with the `equation` environment.

1.8. QUOTATIONS AND FOOTNOTES

Proper quotation formatting improves readability and avoids plagiarism. Short quotations are included inline, for example: According to Einstein, ‘Imagination is more important than knowledge.’

For longer excerpts, use the `quote` environment:

> Science is a way of thinking much more than it is a body of knowledge.
> —Carl Sagan

You may also add explanatory or bibliographic comments using footnotes. For instance, quantum mechanics was formulated in the early twentieth century,[1] which revolutionized physics.

Footnotes should be concise and supplementary, never containing major arguments or references that belong in the bibliography.

[1] Historically, the development involved both matrix mechanics (Heisenberg, 1925) and wave mechanics (Schrödinger, 1926).

PART 2

THEORETICAL BACKGROUND

PART 3

EXPERIMENTAL AND THEORETICAL STUDIES

PART 4

RESULTS AND DISCUSSION

PART 5

CONCLUSION AND FUTURE PLAN

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