Masterexamen med huvudområdet elektronik

*Master of Science (120 credits) with a major in Electronics*

**Thermal Energy Harvesting for Indoor Industrial Applications**

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Abstract

Wireless sensor network (WSN) nodes cannot directly use the traditional power grid, a most common way to supply power to WSN nodes is to use batteries. However, the battery has a disadvantage that is the limited lifetime, adding an energy harvester to extend the lifetime is a good way. The thermoelectric generator is a good choice used for indoor condition since the temperature difference is easy to get in indoor condition, and a higher power density can be obtained, which can reach to $60 \mu W/cm^2$ at $5^\circ C$ gradient.

The thermal energy generator (TEG) consists of the peltier element and the heat sink. The aim of this thesis is to model a TEG in COMSOL Multiphysics and study the characteristic of thermal energy harvesters and the influence of environment variables on thermal energy harvesters in indoor condition.

The results of the thesis show that higher air flow speed at the same temperature gradient or bigger temperature difference at the same air flow speed both can lead to obtain better output performance of the TEG with $1.6 \Omega$ purely resistive load. Using heat sinks also can lead to obtain better output performance of TEG. Different heat sink geometries have been investigated and it is shown that the square angled fin has better performance for cooling down than squared fin and pin fin when comparing the influence of heat sink different structures. Comparing the influence of different air flow directions, the direction of air flow has negligible influence on the pin fin heat sink, but has great influence on the square angled fin heat sink and the squared fin heat sink. Comparing the influence of different heat sink materials, the copper heat sink has almost negligible influence on performance for cooling down than the aluminum heat sink, it is obvious that it has been improved by 4%. For the pin fin heat sinks investigation, with the same size of pin in the same area, the air gap between two pins properly increases, the cooling down performance of pin fin heat sink can be improved by 30%.

Keywords: Thermal energy harvester, Thermal energy generator (TEG), Temperature difference, Air flow, Heat sink, COMSOL Multiphysics
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Mengxuan Li
Sundsvall, Sweden
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# Contents

List of Figures \hspace{1cm} v

List of Tables \hspace{1cm} vii

Abbreviations \hspace{1cm} 1

1 Introduction \hspace{1cm} 2
   1.1 Background and problem motivation \hspace{1cm} 2
   1.2 Purpose of Thesis Work \hspace{1cm} 4
   1.3 Scope of Thesis Work \hspace{1cm} 4
   1.4 Problem Statement \hspace{1cm} 5
   1.5 Thesis Outline \hspace{1cm} 5

2 Related Work \hspace{1cm} 6
   2.1 Thermal energy harvesters for wireless sensor network nodes \hspace{1cm} 6
   2.2 Thermal energy harvesters \hspace{1cm} 6
   2.3 Thermal Energy Harvesters in FEM Simulation \hspace{1cm} 7
   2.4 The Focus of This Thesis Work \hspace{1cm} 7

3 Theory \hspace{1cm} 9
   3.1 Thermal energy harvesting system for WSNs \hspace{1cm} 9
   3.2 Thermoelectric effect \hspace{1cm} 9
      3.2.1 Seebeck Effect \hspace{1cm} 9
      3.2.2 Peltier Effect \hspace{1cm} 10
      3.2.3 Thomson effect \hspace{1cm} 11
   3.3 Thermal energy generator \hspace{1cm} 12
      3.3.1 Materials \hspace{1cm} 12
      3.3.2 Working principle \hspace{1cm} 13
      3.3.3 Main performance parameters \hspace{1cm} 14
   3.4 Peltier Element \hspace{1cm} 15
   3.5 Heat sink \hspace{1cm} 16
   3.6 Finite Element Method \hspace{1cm} 17

4 Methodology \hspace{1cm} 18

5 Implementation \hspace{1cm} 20
   5.1 Experimental setup \hspace{1cm} 20
## Contents

5.2 Geometry Modeling and Materials Selecting ........................................... 22
  5.2.1 Peltier Element Modeling .......................................................... 22
  5.2.2 Purely Resistive Load Modeling .................................................. 23
  5.2.3 Peltier Element with Purely Resistive Load Modeling ...................... 24
  5.2.4 Heat Sink Modeling ....................................................................... 25
    5.2.4.1 Squared Fin Heat Sink ......................................................... 25
    5.2.4.2 Square Angled Fin Heat Sink .............................................. 26
    5.2.4.3 Pin Fin Heat Sink .............................................................. 26
  5.2.5 Heat Source Modeling ..................................................................... 28
  5.2.6 Air Box Modeling .......................................................................... 28

5.3 Characteristic of TEG ........................................................................... 29
  5.3.1 Temperature Difference ............................................................... 29
  5.3.2 Output Power .............................................................................. 29

5.4 Physical Modules Setting ....................................................................... 29
  5.4.1 The Heat Transfer in Solids Interface ........................................... 30
  5.4.2 The Laminar Flow Interface ......................................................... 30
  5.4.3 The Electric Current Interface ...................................................... 31
  5.4.4 Multiphysics Coupling .................................................................. 31
  5.4.5 Meshing ....................................................................................... 31

5.5 Solver Studies and Study Types ............................................................ 32

6 Results ................................................................................................. 33
  6.1 Characteristic of TEG ........................................................................ 33
    6.1.1 Output power of TEG as a function of $v_{Air}$ ......................... 33
    6.1.2 Output power of TEG as a function of $\Delta T_s$ ....................... 34
  6.2 Cooling down performance of Heat sink ............................................ 34
    6.2.1 Material of heat sink ................................................................. 34
    6.2.2 Structure of Heat sink .............................................................. 38
    6.2.3 The influence of air flow direction on heat sink ....................... 39
  6.3 Pin fin heat sink study ........................................................................ 40

7 Summary and Conclusion ...................................................................... 43
  7.1 Thesis conclusions ............................................................................ 43
  7.2 Discussion of Contributions .............................................................. 44
  7.3 Future Work ...................................................................................... 44

Bibliography ............................................................................................. 45
List of Figures

1.1 Components of a WSN node [1] ............................................. 2
3.1 Thermal energy harvesting system for WSNs [2] .................... 9
3.2 Schematic diagram of Seebeck effect [3] ............................... 10
3.3 Schematic diagram of Peltier effect [3] ................................. 11
3.4 Schematic diagram of Thomson effect [3] ............................... 11
3.5 Thermoelectric figure of merit [4] ....................................... 13
3.6 Schematic diagram of the working principle of thermoelectric energy generator [5] ......................................................... 13
3.7 Simple model of thermoelectric energy generator [6] ............... 14
3.8 P-type and n-type semiconductor of peltier element [7] .......... 16
3.9 The work flow of FEM [9] .................................................. 17
5.1 Matlab based experimental setup ......................................... 21
5.2 Simplified module of experimental setup .............................. 22
5.3 Peltier element ............................................................... 22
5.4 A couple of P- and N-type semiconductor in COMSOL .......... 23
5.5 Determining match load in COMSOL ................................... 23
5.6 Purely resistive load in COMSOL ....................................... 24
5.7 Peltier element with purely resistive load in COMSOL .......... 25
5.8 Squared fin heat sink ....................................................... 25
5.9 Square angled fin heat sink ................................................. 26
5.10 Pin fin heat sink with 64 pins in COMSOL ............................ 27
5.11 Pin fin heat sink with 100 pins in COMSOL .......................... 27
5.12 Pin fin heat sink with 225 pins in COMSOL .......................... 28
5.13 Different directions of air flow in COMSOL .......................... 28
5.14 Temperature Difference ................................................ 29
5.15 TEG model circuit ......................................................... 29
5.16 Model meshing in COMSOL ............................................. 32
6.1 $v_{Air} - P_{max}$ curve with $R_L = 1.6 \ \Omega$ ......................... 33
6.2 $\Delta T_s - P_{max}$ curve with $R_L = 1.6 \ \Omega$ ..................... 34
6.3 $v_{Air}$-Difference of three different heat sinks ....................... 35
6.4 $v_{Air}$-Ratio of three different heat sinks ............................ 37
6.5 $\Delta T - P_{out}$ of three different heat sinks ......................... 38
6.6 The $P_{out}$ of different air flow directions for heat sinks .......... 39
List of Figures

6.7 The different numbers of pin fin heat sinks in COMSOL  41
6.8 $\Delta T_s - P_{out}$ at different air flow speed.  42
# List of Tables

1.1 Advantages and disadvantages of energy harvesters [10] .......................... 3
1.3 Performance of energy harvesters under indoor and outdoor condition [11] ................................. 4

4.1 Test cases ...................................................................................... 18
4.2 Indoor condition setting .................................................................. 18

5.1 The category of study [12] ............................................................. 32

6.1 The $P_{\text{out}}$ of different air flow directions for heat sinks ............... 40
6.2 How much percent of $P_{\text{out}}$ lost when the air flow directions changed. 40
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>FEM</td>
<td>Finite Element Method</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>RTD</td>
<td>Resistance-to-Digital Converter</td>
</tr>
<tr>
<td>SCPI</td>
<td>Standard Commands for Programmable Instruments</td>
</tr>
<tr>
<td>SCPI</td>
<td>Standard Testing Condition</td>
</tr>
<tr>
<td>TEG</td>
<td>Thermal Energy Generator</td>
</tr>
<tr>
<td>UI</td>
<td>User Interface</td>
</tr>
<tr>
<td>USB</td>
<td>Universal Serial Bus</td>
</tr>
<tr>
<td>WBAN</td>
<td>Wireless Body Area Network</td>
</tr>
<tr>
<td>WSN</td>
<td>Wireless sensor network</td>
</tr>
</tbody>
</table>
1

Introduction

This chapter describes the background, motivation, purpose, scope and outline about the thesis.

1.1 Background and problem motivation

Wireless sensor network has been more and more widely used in our daily life, such as human health care [13], forest fire monitoring [14], and environmental monitoring [1]. Typically, the WSN is constructed by several wireless sensor nodes. Commonly, as shown in Fig. 1.1, a node is built by following six units, namely sensors, memory, processor, GPS, radio transceiver and power source [15].

![Figure 1.1: Components of a WSN node [1].](image)

For power source, WSN nodes cannot directly used by the traditional power grid [16], a most common way to supply power to WSN nodes is to use batteries. However, the battery has a disadvantage that is the limited lifetime [17]. How to extend the lifetime of batteries or how to replace the batteries are the key problems to extend the lifetime of WSN nodes. In order to replace using batteries or extend the lifetime of the battery, one way is adding an energy harvester to the WSN node [18]. An energy generator can convert non-electrical power to electrical power, and supply to WSN nodes [19].
There are some advantages and disadvantages when using the energy harvester for powering WSN nodes and mobile devices, which are listed in Tab. 1.1.

**Table 1.1:** Advantages and disadvantages of energy harvesters [10].

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extend the lifetime of WSN nodes when they are used with energy harvester together</td>
<td>May cause that the energy harvester can’t provide sufficient power for WSN node</td>
</tr>
<tr>
<td>Without pay more attention on maintain of battery replacement</td>
<td>Power density and efficiency depend on different elements</td>
</tr>
</tbody>
</table>

There are many different kinds of the energy harvesters [20]. Most of them convert electrical energy from light [21], vibrations [22] and temperature difference [23]. For example, solar panel harvests energy from sun’s rays, and converts them to electric power [21]. Some energy sources and harvesters are listed in Tab. 1.2.

**Table 1.2:** Characteristics of indoor energy source [11].

<table>
<thead>
<tr>
<th>Indoor Energy Source</th>
<th>Characteristics</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar</td>
<td>Intermittent</td>
<td>Illumination from artificial lighting during office hours</td>
</tr>
<tr>
<td>Wind</td>
<td>Continuous</td>
<td>Air circulation from air conditioner and electric fans</td>
</tr>
<tr>
<td>Thermal</td>
<td>Continuous/ Intermittent</td>
<td>Thermal gradient between body, machine heat and ambient</td>
</tr>
<tr>
<td>Vibration</td>
<td>Intermittent</td>
<td>Vibration from machine and human motion during walking, running, etc.</td>
</tr>
</tbody>
</table>

According to Tab. 1.2 and Tab. 1.3, compared these energy sources and power densities of different energy generators, the thermoelectric generator is suited for indoor condition. Because the temperature difference can be controlled easily, and higher power density can be achieved.
1. Introduction

Table 1.3: Performance of energy harvesters under indoor and outdoor condition [11].

<table>
<thead>
<tr>
<th>Energy Harvester</th>
<th>Power Densities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Indoor Condition</td>
</tr>
<tr>
<td>Solar Panel</td>
<td>100 $\mu$W/cm$^2$ @ 100 W/cm$^2$</td>
</tr>
<tr>
<td>Wind Turbine Generator</td>
<td>35 $\mu$W/cm$^2$ @ &lt; 1 m/s</td>
</tr>
<tr>
<td>Thermoelectric Generator</td>
<td>60 $\mu$W/cm$^2$ @ 5 $^\circ$C</td>
</tr>
<tr>
<td>Electromagnetic Generator</td>
<td>4 $\mu$W/cm$^2$ @ human motion-Hz</td>
</tr>
<tr>
<td></td>
<td>800 $\mu$W/cm$^2$ @ machinen-KHz</td>
</tr>
<tr>
<td></td>
<td>Outdoor Condition</td>
</tr>
<tr>
<td></td>
<td>10 mW/cm$^2$ @ STC</td>
</tr>
<tr>
<td></td>
<td>3.5 mW/cm$^2$ @ 8.4 m/s</td>
</tr>
<tr>
<td></td>
<td>3.5 mW/cm$^2$ @ 30 $^\circ$C</td>
</tr>
</tbody>
</table>

The thesis is going to use finite element method (FEM) simulation to estimate the influence of environment factors on TEG output performance at different temperature gradient in indoor condition, especially study the influence of air flow speed and different heat sinks on TEG output performance.

1.2 Purpose of Thesis Work

The purpose of this thesis work is to model and combine all components to build an experimental setup in COMSOL Multiphysics and study the performance of TEG at different temperature gradient with low air flow speeds and directions in indoor condition. Some details are listed below.

- Modelling components in COMSOL, such as peltier element and heat sinks, to verify the internal resistor and the purely resistive load.
- Combine all components to build an experiment setup in COMSOL to study the output performance of TEG in indoor condition.
- Study the TEG performance for different environmental conditions.
- Study how much output power can be collected from TEG in real indoor condition and in COMSOL.
- Study the influence of the heat sinks.
- Study the influence of the air flow.
- Study characteristics of thermal energy harvesters.

1.3 Scope of Thesis Work

This thesis is focused on using FEM simulation to study the output performance of thermal energy harvesters with different environmental factors. The thermal energy harvester is composed a TEG and a heat sink, in this thesis, all components simulated in COMSOL Multiphysics are the same as all components used in the experimental setup. In order to analyze output performance of the thermal energy harvester, a purely resistive load is connected to the output terminal of TEG. Using four cases, which are without heat sink, square fin heat sink, square angled fin heat sink and pin fin heat sink, has been studied at different temperature gradient in the indoor condition. Here, in indoor condition, the cold temperature is set as 20 $^\circ$C, the range of hot temperature is 25 – 50 $^\circ$C, and the air flow speed range is 0.1 – 0.6 m/s.
1. Introduction

1.4 Problem Statement

The thesis work has an objective to respond to the following questions:
P1: How much output power can be harvested of TEG in indoor condition from simulation?
P2: How much efficiency can be harvested of TEG in indoor condition from simulation?
P3: How do the different structures of heat sinks effect TEG’s output?

1.5 Thesis Outline

Chapter 1, 2 and 3 introduce the background, related work and theory about this thesis work. Chapter 4 and 5 show how to use FEM simulation to study the output performance of the thermal energy harvester. Chapter 6 shows the FEM simulation result. Chapter 7 analyzes the result to obtain the conclusion.

- **Chapter 1** introduces the background about the energy harvesters, and shows motivation, objective, and problem formulation of the master’s thesis.
- **Chapter 2** introduces some related work about building the experimental setup by using FEM simulation in COMSOL Multiphysics.
- **Chapter 3** introduces the theory about thermoelectricity, and gives more detail about TEGs and heat sink.
- **Chapter 4** describes the methods that are used in this thesis, and how to use these methods to achieve the aim.
- **Chapter 5** explains the process of building the experimental setup in COMSOL Multiphysics.
- **Chapter 6** shows the results of thermal energy harvester from COMSOL Multiphysics.
- **Chapter 7** analyses the results to get the conclusion and simple describes the future work.
2
Related Work

This chapter presents some papers which are related to this thesis work.

2.1 Thermal energy harvesters for wireless sensor network nodes

The first paper is named “Thermal Energy Harvesting for WSNs [24]”. This paper describes a thermal energy harvesting system with a low temperature. The module is shown that can get thermal energy from a radiator and uses this model to convert into electric power to power Zig-Bee. The main advantages of this model are high efficiency and a long system lifetime. The results of this module show that a maximum power is 150 mW.

The second paper is named “Thermal Energy Harvesting from Human Warmth for Wireless Body Area Network in Medical Healthcare System [25]”. This paper describes a method based on the residual energy which is provided by the wireless sensor network nodes to select a gateway. The lifetime of the wireless body area network can be prolonged by changing the gateway. To further prolong the lifetime of wireless body area network (WBAN), a thermal energy harvester should be added. This thermal energy harvester can harvest thermal energy from human warmth. The results show that the thermal energy harvester can accumulate energy about 1.369 mJ to supply power to nodes for WBAN.

2.2 Thermal energy harvesters

The first paper is named “Thermal Energy Harvesting with Thermo Life [26]”. This paper describes the thermoelectric converter named Thermo Life, it is a unique, small and compact energy source. In any environment, just exists temperature difference can enable this kind of thermal converter. This thermal energy harvester can produce the output power from a few 10 µW to 100 µW.

The second paper is named “Power and Efficiency Measurement in a Thermoelectric Generator [27]”. This paper describes using an experimental setup to measure the efficiency of the thermoelectric generator. The thermoelectric devices can convert a difference in temperature into electricity, this characterization relies on the Seebeck effect. Thermoelectric devices are usually used for a number of different current applications, such as waste heat recovery. In this experiment, the author designs the data acquisition system by LabVIEW to measure real-time efficiency of
the thermoelectric device under the different testing conditions. The two results, which are from this paper, one is that increasing the heater voltage increased the temperature difference across the device. Another is that the efficiency increases with increasing change in temperature and with the highest temperature changed.

2.3 Thermal Energy Harvesters in FEM Simulation

The first paper is named “3D-Model of Asymmetric Thermo-Electric Generator Modules for High Temperature Applications [28]”. This paper describes the modelling and simulation of the asymmetric thermo-electric module in COMSOL Multiphysics. This module has a larger temperature range than other high-temperature modules, because of its novel design. The materials of this novel module are boron carbide and titanium diboride, these materials are developed for using in high temperature range. The results of this work, the thermal and electric performance of this module can be presented well in COMSOL Multiphysics.

The second paper is named “Multiphysics Simulation of Thermoelectric Systems - Modeling of Peltier-Cooling and Thermoelectric Generation [29]”. This paper describes using COMSOL Multiphysics to show an implementation of thermoelectric field equations. The results of this paper present a good way to study thermo-electric systems. In COMSOL Multiphysics, thermoelectric calculation can be made, and it is easy to add structural analysis or convection.

The third paper is named “Considering Thermoelectric Power Generation Device Efficiency Using Micro-Channel Heat Sink [30]”. This paper describes using a micro-channel heat sink to increase TEG efficiency and compared the result with a same dimension heat sink in macro-scale. The result of this work, the micro-channel heat sink significantly increase TEG power generated and energy efficiency.

2.4 The Focus of This Thesis Work

In the preparatory work of this thesis, many valuable comments can be found in these papers.

The thermal energy harvester is a good choice to extend lifetime of batteries for powering WSN node in indoor condition. It includes the thermal energy generator and the heat sink [31]. The peltier element is used as a TEG, it can convert the thermal energy into the electric power directly, and also can convert the electric power into thermal energy. It is based on thermoelectric effect [32]. Heat sink is a passive heat exchanger, it is based on heat transfer principle. Different heat sinks have different performances for cooling down [33].

Finite element method is a good numerical technique. FEM divides a large problem into smaller and simpler parts. The simple equations are used to model finite elements, and these simple equations are assembled into a large system to model the whole problem. FEM uses variational methods to approximate a solution [34]. COMSOL Multiphysics is a FEM software package, it is used for various physics
and engineering applications [35].

In the thesis work, modelling and simulation thermal energy harvester which includes peltier element and three different structures of heat sinks in COMSOL Multiphysics to analyze the influence of environment factors on thermal energy harvester output performance.
3

Theory

In the following sections, the theory behind the different parts used in the design of the thesis work will be described briefly.

3.1 Thermal energy harvesting system for WSNs

The thermal energy harvesting system [2] consists of the thermal energy generator, the heat sink, voltage regulation, charge management and energy storage, and heat source. The Fig. 3.1 depicts the thermal energy harvesting system.

![Thermal energy harvesting system for WSNs](image)

Figure 3.1: Thermal energy harvesting system for WSNs [2].

3.2 Thermoelectric effect

Thermoelectric effect consists of three separately identified effects, and they, which are Seebeck effect, Peltier effect, and Thomson effect. Relaying on the thermoelectric effect the conversion of thermal energy to electric power can be achieved [36].

3.2.1 Seebeck Effect

The Seebeck effect [36] can convert the temperature difference directly into electric power at the different type junctions of wire. When put a compass near a closed
loop that is consisted of two different type conductors, if between the joints exists temperature difference, the compass would be deflected. A subsequent study found that in the closed loop, it exists electromotive force. This electromotive force is named Seebeck electromotive force, and it is called Seebeck effect.

![Figure 3.2: Schematic diagram of Seebeck effect [3].](image)

The Fig. 3.2 depicts the schematic diagram of Seebeck effect. This is a circuit made up of two different type conductors. When the temperature difference $\Delta T$ is existed between point $A$ and point $B$, the Seebeck electromotive force $\Delta U$, also called thermoelectric power, is produced between point $X$ and point $Y$. The thermoelectric power $\Delta U$ is proportional to the temperature difference $\Delta T$. The proportionality constant is named Seebeck coefficient $\alpha$, and it is also named as a thermoelectric coefficient, and $\alpha$ is expressed by,

$$\alpha_{1,2} \approx \lim_{\delta T \rightarrow 0} \frac{\delta U}{\delta T} = \frac{dU}{dT} \quad [36].$$

For at the room temperature, the Seebeck coefficient of ordinary materials is in the range of $-100 - 1000 \, \mu V/K$.

### 3.2.2 Peltier Effect

The Peltier effect [37] can convert the electric power directly into temperature difference, and present heating or cooling at the junctions of two different type conductors. Using two different type conductors to make a thermocouple, and then connecting with a current source. When current flows through the junction between two different type conductors, the electric energy transfers into the thermal energy. One point turns heat because it is releasing heat, and another point absorbs heat and becomes cold. Which side becomes heat (or cold) depends on the direction of current flow. This phenomenon is called Peltier effect.
3. Theory

The Fig. 3.3 depicts a schematic diagram of Peltier effect. If current flows through the junction between two different type conductors, one point becomes heat, and another point becomes cold. Assuming the rate of absorbing heat (or releasing heat) is $Q$, the rate of absorbing heat (or releasing heat) $Q$ is proportional to the current $I$ in the loop, $Q$ is expressed by,

$$Q = \pi_{12} I \ [37],$$

(3.2)

where $\pi_{12}$ is Peltier coefficient, and it is a proportionality constant,

$$\pi_{12} = \frac{Q}{I}.$$  

(3.3)

Obviously, the Peltier coefficient stands for how much absorbed heat (or released heat) is carried per unit charge in pre-unit time.

### 3.2.3 Thomson effect

The Thomson effect [33] can transfer energy between conductor and ambient environment when the current flows through the conductor that has the temperature gradient.

The Fig. 3.4 depicts a schematic diagram of Thomson effect. Supposing the current which flows through the conductor is $I$, the temperature difference is $\Delta T = T_1 - T_2$, the rate of absorbing heat (or releasing heat) in this conductor $Q_t$ is expressed by,
3. Theory

\[ Q_t = \beta I \Delta T \] \[ (3.4) \]

where \( \beta \) is a proportionality constant, and defined as Thomson coefficient,

\[ \beta = \frac{Q_t}{I \Delta T}. \] \[ (3.5) \]

When the direction of current flow is same as the temperature gradient, if the conductor absorbs heat, the Thomson coefficient is positive and vice versa.

The relationship between Seebeck coefficient \( \alpha_{ab} \), Peltier coefficient \( \pi_{ab} \) and Thomson coefficient \( \beta_{a,b} \) is expressed by,

\[ \alpha_{ab} = \frac{\pi_{ab}}{T}, \] \[ (3.6) \]

\[ \frac{d\alpha_{ab}}{dT} = \frac{\beta_a - \beta_b}{T}. \] \[ (3.7) \]

3.3 Thermal energy generator

A thermoelectric generator [38], is called a Seebeck generator. This device can convert the temperature difference directly into the electric power, which relies on Seebeck effect that is one of the thermoelectric effect. Typically, TEGs are more expensive and less efficient.

3.3.1 Materials

TEG convert the temperature difference directly into the electric power, so the materials of TEG must have high electrical conductivity and low thermal conductivity. Some semiconductors are regarded as TEG materials, such as \( PbTe \), \( SiGe \), and \( Bi_2Te_3 \) [39]. Figure of merit value (ZT) is an important parameter of thermoelectric materials, it determines the efficiency of a given material to convert heat into electricity. ZT value is expressed by,

\[ Z = \frac{\alpha^2 \sigma}{k T}, \] \[ (3.8) \]

where \( \sigma \) and \( k \) are electrical conductivity and thermal conductivity of thermoelectric material [40].

The ZT value of thermoelectric materials is summarized in Fig. 3.5. In this figure, \( Bi_2Te_3 \) is the most popular thermoelectric material to use below 200 °C [4].
3. Theory

3.3.2 Working principle

The Fig. 3.6 depicts a schematic diagram of the working principle of TEGs.

A thermal energy harvester consists of two thermoelectric semiconductors named n-type subjected and p-type subjected to temperature difference $\Delta T = T_{\text{hot}} - T_{\text{cold}}$, and connects with an electric source in series through the conductor on the top and bottom. In the n-type (or p-type) subjected thermoelectric semiconductor, most charge carriers are negative charged electrons, the other one most of the carriers are positive charged holes. In a temperature gradient, electrons and holes from the hot side tend to accumulate on the cold side. Between the hot side
and the cold side of each material, an electric field $E$ is produced, which gives a voltage. The voltages of the n-type subjected thermoelectric semiconductor and p-type subjected thermoelectric semiconductor add up and drive a current through an electrical load. The voltage and the current are the electric output power of this thermal energy harvester [5].

### 3.3.3 Main performance parameters

The Fig. 3.7 shows a simple model of thermoelectric energy generator [6]. This simple model of thermoelectric energy generator consists of a couple of thermocouple that is made up of the n-type subjected thermoelectric semiconductor and p-type subjected thermoelectric semiconductor. If this simple model is seen as an ideal unit, the formulas of the main performance parameters can be deduced.

![Figure 3.7: Simple model of thermoelectric energy generator [6].](image)

The Seebeck electromotive force $U$ in this loop is expressed by,

$$U = \alpha(T_h - T_c).$$  \hspace{1cm} (3.9)

Add this electromotive force $U$ to the generator’s internal resistance $r$ and an electric load $R$, the real output voltage $U_0$ is equal to this electromotive force $U$ add to an electric load $R$. So the real output voltage $U_0$, the real output current $I_0$ and the real output power $P_0$ in this loop are expressed by,

$$U_0 = \alpha(T_h - T_c)\frac{R}{R + r},$$  \hspace{1cm} (3.10)

$$I_0 = \frac{\alpha(T_h - T_c)}{R + r},$$  \hspace{1cm} (3.11)

$$P_0 = U_0I_0,$$  \hspace{1cm} (3.12)

$$P_0 = \frac{\alpha^2(T_h - T_c)^2R}{(R + r)^2}.$$  \hspace{1cm} (3.13)
The hot side of the thermal energy generator absorbs heat $Q_h$, it is expressed by,

$$Q_h = \alpha T_h I - \frac{1}{2} I^2 r + \lambda(T_h - T_c), \quad (3.14)$$

where $\lambda$ is thermal conductivity.

So the efficiency $\eta$ is expressed by,

$$\eta = \frac{P_0}{Q_h}, \quad (3.15)$$

$$\eta = \frac{\alpha^2(T_h - T_c)^2 R/(R + r)^2}{\alpha T_h I - \frac{1}{2} I^2 r + \lambda(T_h - T_c)}. \quad (3.16)$$

Suppose $m = R/r$, $d\eta/dm = 0$, when the thermal energy generator reaches the maximum efficiency,

$$m = \frac{R}{r}, \quad (3.17)$$

$$m = \sqrt{(1 + Z T)}. \quad (3.18)$$

Where $T$ is the average temperature of hot side temperature and the cold side temperature,

$$\bar{T} = \frac{(T_h + T_c)}{2}. \quad (3.19)$$

So the maximum efficiency $\eta_{max}$ is expressed by,

$$\eta_{max} = \frac{(T_h - T_c)}{T_h} \times \frac{\sqrt{(1 + Z T)} - 1}{\sqrt{(1 + Z T)} + T_c/T_h}. \quad (3.20)$$

In the same manner, suppose $dP_0/dm = 0$, when $m = R/r = 1$, it means an electric load is the same as the inter resister of the thermal energy generator, the output power can get maximum value. The maximum output power $P_{max}$ is expressed by,

$$P_{max} = \frac{\alpha^2(T_h - T_c)^2}{4r}, \quad (3.21)$$

$$P_{max} = \frac{\alpha^2 \Delta T}{4r}. \quad (3.22)$$

### 3.4 Peltier Element

Peltier element is regarded as TEG, this device can convert the thermal energy into the electric power directly, and it also can convert the electric power into thermal energy. It is based on thermoelectric effect [32].
3. Theory

Peltier element generates a voltage $V_{th}$ when it subjects to a temperature difference $\Delta T$, if peltier element connects to a resistive load $R_{load}$, an electric current $I$ will flow the $R_{load}$. The power $P$ is determined by $I$ and $V$. It should be noted that Peltier element has internal resistance $R_{in}$, it is not an ideal voltage source, and must be considered when analysis the power [41].

The Fig. 3.8 shows the construction of peltier element. Between two ceramic insulators, alternating p-type and n-type semiconductors are used copper junctions to connect them electrically in series and thermally in parallel [7].

![Figure 3.8: The construction of peltier element [7].](image)

The Fig. 3.8 shows a series of alternating p-type and n-type semiconductor of peltier element [8].

![Figure 3.9: P-type and n-type semiconductor of peltier element [8].](image)

3.5 Heat sink

The heat sink is a passive heat exchanger, it based on heat transfer principle [33]. They can transfer heat generated into a cool medium in motion, the heat leaves devices with the cool medium, therefore the device temperature has regulated at physically feasible levels [42]. Because heat sink has the fin structure, it can maximize the surface area in contact between the thermal interface material and ambient cool medium, such as the air. Some factors can affect the performance of the heat sink, such as air velocity, material of heat sink, structure of heat sink, surface treatment and attachment methods. To avoid the air gaps between the heat sink and the thermal device, thermal adhesive or thermal grease are good choices.
3. Theory

3.6 Finite Element Method

Finite element method is a good numerical technology, a large problem is divided into smaller and simpler parts to model by using simple equations, and then these simple equations are assembled into a large system to model the whole problem. FEM uses variational methods to approximate a solution [9]. The work flow of FEM is depicted in 3.10.

![Figure 3.10: The work flow of FEM [9].]
4
Methodology

The main method of this thesis work is finite element method (FEM). Based on the experimental setup that is designed in the first project [43], all components are rebuild as 1:1 scale in COMSOL Multiphysics to study output performance of TEG in an ideal indoor condition. The steps of modelling experimental setup in COMSOL Multiphysics are listed below.

- Creating 3D geometry, and enter the parameters of each settings. Parameter definitions should be the same as object’s parameters.
- Add the materials for geometry model.
- Add physics and couple them. In the master thesis, the TEG modelling uses heat transfer in solids, heat transfer in fluids, and electromagnetic heating.
- Mesh settings. Choose the sequence type and element size for each domain. The element size affects the speed of computing and the accuracy of the result.
- Study settings. Choose study type and compute.
- Result. Analysis the result.

In this thesis work, there are four different cases which have tested in this thesis listed in Tab. 4.1, and indoor condition setting is listed in Tab. 4.2.

Table 4.1: Test cases.

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case Number</td>
<td>Structure of Heat Sink</td>
</tr>
<tr>
<td>1</td>
<td>No heat sink</td>
</tr>
<tr>
<td>2</td>
<td>Square fin heat sink (copper and alumina)</td>
</tr>
<tr>
<td>3</td>
<td>Square angled fin heat sink (copper and alumina)</td>
</tr>
<tr>
<td>4</td>
<td>Pin fin heat sink (copper and alumina)</td>
</tr>
</tbody>
</table>

Table 4.2: Indoor condition setting.

<table>
<thead>
<tr>
<th>Hot Temperature</th>
<th>25 – 50 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>step: 5 °C</td>
<td></td>
</tr>
<tr>
<td>Air Flow Speed</td>
<td>0.1 – 0.6 m/s</td>
</tr>
<tr>
<td>(Direction of air flow: 0°, 45°, 90°)</td>
<td></td>
</tr>
<tr>
<td>Air Temperature</td>
<td>20 °C</td>
</tr>
</tbody>
</table>
Considering the internal resistor of the peltier element, a purely resistive load is connected to the output terminal of peltier element. The resistance of the load is 1.6 \, \Omega because \( R_{\text{in}} \) is 1.6 \, \Omega by measurement.
This chapter describes how to build the TEG experimental setup in COMSOL Multiphysics.

5.1 Experimental setup

The whole system of this experimental setup is divided into 4 parts, including the air temperature controlling and measurement system, the temperature of the TEG’s two sides controlling and measurement system, the output parameters of the thermal energy harvester controlling and measurement system, and user interface [43].

In this experimental setup, for hardware, the temperature chamber, where all components put in, is needed to keep the air temperature stable. One peltier element is used as a TEG, it can convert temperature difference into voltage, and another peltier element is used as a heater, it needs a power supply to provide the input voltage to produce temperature difference between their two sides, the hot side supplies the hot temperature to TEG’s hot side. The heat sink is used to release heat from TEG’s cold side and diminish the influence of hot side to the cold side. Two temperature sensors, pt100, are used to measure the temperature of TEG’s two sides. The RTD can transfer resistance to digital to the Arduino board, and the Arduino board is used to read the real time temperature. The whole software system is based on using Matlab. First of all, to achieve the communication between computer and devices, it is a way to use the serial communication. The temperature chamber and the power supply both use RS-232 port to connect with computer. The multimeters and Arduino board use USB port to connect with computer. In the serial communication, SCPI command is easy to use. SCPI stands for Standard Commands for Programmable Instruments, defines a standard for the syntax and commands to use in controlling programmable measurement devices. Secondly, in this system, the temperature chamber, the power supply, two multimeters and Arduino board need to be controlled by Matlab. For temperature chamber, the Matlab is used to set temperature and read real time temperature. For power supply, the Matlab is used to control the temperature of heater. For Arduino board, the Matlab is used to read the real time temperature of TEG’s two sides to get the certain temperature difference between TEG’s two sides. For multimeters, the Matlab is used to measure output voltage and output current at the same time. This software system makes the experimental setup automatic. And the Matlab is also used to create a user interface to make this setup use easily. The Fig. 5.1 shows the Matlab based experimental setup.
Figure 5.1: Matlab based experimental setup.
5. Implementation

In real indoor condition, it is difficult to control the parameters, the main problems are the uniform $v_{\text{Air}}$ controlling and $T_{\text{hot}}$ and $T_{\text{cold}}$ measurement, because the uniform $v_{\text{Air}}$ and constant $\Delta T$ are needed during the testing. The COMSOL Multiphysics can be used to set the uniform $v_{\text{Air}}$ and keep $\Delta T$ constantly, that means the main problems can be solved. The part two of experimental setup shown in Fig. 5.2 is modelled and simulated in COMSOL Multiphysics.

![Air Box](image)

Figure 5.2: Simplified module of experimental setup.

5.2 Geometry Modeling and Materials Selecting

The 3D-model in COMSOL Multiphysics is build as 1:1 scale according to the TEG experimental setup.

5.2.1 Peltier Element Modeling

This peltier element is made of Bismuth Telluride semiconductor material and thermally conductive Aluminum Oxide ceramics shown in Fig. 5.3a. The physical size is $30 \text{mm} \times 34 \text{mm} \times 3.3 \text{mm}$. The Fig. 5.3b shows the peltier element modeling in COMSOL.

![Photo of peltier element](image)

(a) Photo of peltier element.

![Peltier element in COMSOL](image)

(b) Peltier element in COMSOL.

Figure 5.3: Peltier element.
There are 71 couples of P-type and N-type semiconductor between ceramic insulators, and alternating p-type and n-type semiconductors are used copper junctions to connect them electrically in series and thermally in parallel. The Fig. 5.4 shows a couple of P- and N-type semiconductor between ceramic insulators.

**Figure 5.4:** A couple of P- and N-type semiconductor in COMSOL.

### 5.2.2 Purely Resistive Load Modeling

The peltier element has the internal resistor, it is measured as $1.6 \, \Omega$ when the experimental setup is built. The Fig. 5.5 shows the match load determined in COMSOL, it is obvious that the match load resistance can be found when the maximum power point of the peltier element measured, it is approximate $1.5 - 1.6 \, \Omega$, and it is equal to the resistance of the peltier element internal resistor.

**Figure 5.5:** Determining match load in COMSOL.

The Fig. 5.6 shows purely resistive load modeling in COMSOL.
5. Implementation

Figure 5.6: Purely resistive load in COMSOL.

The purely resistive load is connected to the output terminal of peltier element. The resistance $R$ can be calculated by,

$$R = \rho \frac{l}{A}, \quad (5.1)$$

where $l$ is the length of conductor, $A$ is the cross area of the conductor, $\rho$ is the electrical resistivity.

The electrical resistivity can be expressed by,

$$\rho = \frac{1}{\sigma}, \quad (5.2)$$

where $\sigma$ is the electrical conductivity.

In order to calculate resistance easily, the length of conductor is 10 mm, the cross area is 10 mm$^2$, the resistance can be expressed by,

$$R = 1000 \frac{1}{\sigma}. \quad (5.3)$$

Therefore, changing the electrical conductivity of conductor material can change the resistance of a conductor. In this thesis work, using a user-defined material for purely resistive load can achieve the resistance variation.

5.2.3 Peltier Element with Purely Resistive Load Modeling

In order to decrease the effect of the internal resistor, the external purely resistor with 1.6 $\Omega$ should be connected. The Fig. 5.7 shows peltier element with a purely resistive load in COMSOL Multiphysics simulation at z-x view.
5.2.4 Heat Sink Modeling

The materials of three different heat sinks are copper and aluminum.

5.2.4.1 Squared Fin Heat Sink

The Fig. 5.8a shows the photo of square fin heat sink. The physical size is \(30\ mm \times 30\ mm\). It has 8 fins and the height of each fin is \(19.5\ mm\). The Fig. 5.8b shows squared fin heat sink in COMSOL Multiphysics simulation at x-y view.

\(\text{Figure 5.7: Peltier element with purely resistive load in COMSOL.}\)

\(\text{Figure 5.8: Squared fin heat sink.}\)
5.2.4.2 Square Angled Fin Heat Sink

The square angled fin heat sink is depicted in Fig. 5.9a. The physical size of top surface is 59 mm $\times$ 30 mm, and the physical size of bottom surface is 30 mm $\times$ 30 mm. It has 10 fins and the height of each fin is 19.5 mm. The Fig. 5.9b shows square angled fin heat sink in COMSOL Multiphysics simulation at x-y view.

Figure 5.9: Square angled fin heat sink

5.2.4.3 Pin Fin Heat Sink

The physical size of the pin fin heat sink is 30 mm $\times$ 30 mm, the height of each pin is 19.5 mm. The Fig. 5.10 shows pin fin heat sink with 64 pins in COMSOL Multiphysics simulation at 3D view. The size of top surface for each pin is 2 mm $\times$ 2 mm, and the distance between two pins is 2 mm.
5. Implementation

Figure 5.10: Pin fin heat sink with 64 pins in COMSOL.

The Fig. 5.11 shows pin fin heat sink with 100 pins in COMSOL Multiphysics simulation at 3D view. The physical size of the pin fin heat sink is 30 $mm \times 30 \ mm$, the height of each pin is 19.5 $mm$. The size of top surface for each pin is 2 $mm \times 2 \ mm$, and the distance between two pins is 1 $mm$.

Figure 5.11: Pin fin heat sink with 100 pins in COMSOL.

The Fig. 5.12 shows pin fin heat sink with 225 pins in COMSOL Multiphysics simulation at 3D view. The physical size of the pin fin heat sink is 30 $mm \times 30 \ mm$, the height of each pin is 19.5 $mm$. The size of top surface for each pin is 1 $mm \times 1 \ mm$, and the distance between two pins is 1 $mm$. 
5. Implementation

Figure 5.12: Pin fin heat sink with 225 pins in COMSOL.

5.2.5 Heat Source Modeling

In order to analyze easily, the geometry modelling of heat source is set very thin, which can be regarded as a surface to contact with peltier element hot side. The size of heat source is $30 \text{ mm} \times 34 \text{ mm}$, and the temperature of heat source can change from $25 \degree C$ up to $50 \degree C$.

5.2.6 Air Box Modeling

The size of air box is $40 \text{ mm} \times 45 \text{ mm} \times 50 \text{ mm}$, and the air box is full of air. In the 3D-model, all components except heat source and purely resistive load are put in the air box. There are three different air flow directions shown in Fig. 5.13 when testing. The $0\degree$ direction is defined as perpendicular to the external purely resistive load. The $90\degree$ direction is defined as parallel to the external purely resistive load.

Figure 5.13: Different directions of air flow in COMSOL.
5.3 Characteristic of TEG

There are two important definitions of TEG used for result analysis.

5.3.1 Temperature Difference

The two kinds of temperature difference are used in this thesis. One is defined as $\Delta T$ that is $T_{\text{hot}} - T_{\text{cold}}$, another is defined as $\Delta T_s$ that is $T_{\text{hot}} - T_{\text{Air}}$. The Fig. 5.14 shows the different temperatures which are used.

![Figure 5.14: Temperature Difference.](image)

5.3.2 Output Power

When output power of TEG is measured, it should consider the influence of its internal resistor. As mentioned before, in order to decrease its influence, the purely resistive load should be connected to the external terminal of TEG. The Fig. 5.15 depicts the TEG model circuit. In Fig. 5.15, $R_i$ is the internal resistor, $R_L$ is match load.

![Figure 5.15: TEG model circuit.](image)

5.4 Physical Modules Setting

Many physical modules can be chosen in COMSOL. The optional COMSOL modules are optimized for specific application areas and these optional modules provide standard terminology of discipline and physics interfaces [12]. AC/DC module, CFD module and Heat Transfer module are used for this thesis work. A short description of these modules is listed below.
5. Implementation

- AD/DC module: it provides a unique environment for AC/DC electromagnetics simulation. It is used to analyze coils, capacitors, and electrical machinery. In this thesis, the physics interfaces is named the electric currents interface (ec).
- CFD module: it supports the customized UI and functionality optimized to analyze all kinds of fluid flow. In this thesis, the physics interfaces is named the laminar flow interface (spf).
- Heat transfer module: All heat transfer basic mechanisms are supported in this module. In this thesis, the physics interfaces is named the heat transfer in solids interface (ht).

5.4.1 The Heat Transfer in Solids Interface

The heat transfer in solids interface is used to model heat transfer in solids by convection, conduction, surface-to-surface radiative heat transfer and surface-to-ambient radiation radiative heat transfer, it is active by default on all domains. According to the differential form of the Fourier’s law, the temperature equation is defined in solid domains [12]. In the thesis, it is used for thermal energy harvester with purely resistive load.

- Heat transfer in solids: this node uses the heat equation to model heat transfer in solids. In this thesis, it is used for heat sink, peltier elements, cables and purely resistive load.
- Initial values: this node is used to set an initial value for temperature which can be seen as an initial condition for a heat transfer simulation. In this thesis, the initial value of temperature is \(20 \, ^\circ C\).
- Thermal insulation: this node is used to set boundary condition for all interfaces which are used for heat transfer. This boundary condition is defined where the domain is well insulated since there is no heat flux across the boundary. In this thesis, it is used for heat sink, peltier element (except hot side), cables and purely resistive load.
- Outflow: This node is used to set the outlet boundaries for heat transfer. In this thesis, it is used to set one surface of air box to show air flow outlet.
- Temperature 1 and 2: This node is used to set the temperature in the geometry. In this thesis, temperature 1 is used to set the temperature as \(20 \, ^\circ C\) to all components without the hot side of peltier element. Temperature 2 is used to set the temperature range \(25 - 50 \, ^\circ C\) to hot side of peltier element.

5.4.2 The Laminar Flow Interface

The laminar flow interface is used to compute the pressure and velocity field for a single phase fluid flow. The equations solved by laminar flow interface are defined according to the Navier-Stokes equations for conservation of momentum and the continuity equation for conservation of mass [12]. In the thesis, it is used to define the air box.

- Fluid properties: this node provides the momentum and continuity equations and the interface used for the material defined of the fluid. In this thesis, it is
used for air box.

- **Initial values:** this node is used to set an initial values in a stationary walls. In this thesis, it is used to set the velocity field and pressure.

- **Wall:** this node uses to describe fluid flow boundary conditions for stationary, moving, and leaking wall. In this thesis, it is used to set the surface of air box without inlet and outlet as walls.

- **Inlet:** it is used on the boundary for the domain which has a net flow into. When defined the inlet condition, the outlet condition should be considered. In this thesis, it is used to set one surface of air box as inlet.

- **Outlet:** it is used on the boundary for the domain which has a net flow into. When defined the outlet condition, the inlet condition should be considered. In this thesis, it is used to set one surface of air box as outlet.

### 5.4.3 The Electric Current Interface

The electric current interface is used to compute current, potential distributions and electric field in conducting media. Based on Ohm’s law, a current conservation is solved when the dependent variable is scalar electric potential [12]. In the thesis, it is used to define the purely resistive load.

- **Current conservation:** this node is used for the electrical potential by adding the continuity equation and it provides an interface to define the electric conductivity as well as the constitutive relation and the relative permittivity for the displacement current. In this thesis, it is used for the purely resistive load.

- **Electric insulation:** this node is used to define the electric insulation boundary condition. That means there is no current flows into this boundary. In this thesis, it is used for the purely resistive load.

- **Initial values:** this node is used to set an initial value for the electric potential. In this thesis, it is used to set electric potential.

- **Ground:** this node is used to set $V = 0$ for the boundary condition as ground. That means there is a zero potential on this boundary. In this thesis, it is used to set one of the purely resistive load port as ground.

- **Terminal:** this node is used to set the boundary condition to connect with external circuits, transmission lines, or the specified voltage or current. It is also can used to compute the impedance. In this thesis, it is used to set another port of the purely resistive load as terminal.

### 5.4.4 Multiphysics Coupling

The multiphysics coupling is used to couple physics features for coupled field analysis [12]. In COMSOL, there are no settings required for node itself, it is added automatically when COMSOL recognizes that the model has a logical coupling internet.

### 5.4.5 Meshing

The feature of the mesh is to enable the discretization of the geometry model into small units with simple shapes [12]. The size of mesh element effects the compu-
tational time and result accuracy. In the thesis, different components use different mesh size. The size of air box uses extra coarse level shown in Fig. 5.16a, because the final analyses do not require the result from air box. Because the geometry model of peltier element and heat sink are very complex, in order to shorten the computational time, the size of these use normal level shown in Fig. 5.16b. In order to improve the simulation result accuracy, the size of purely resistive load and cables use extremely fine level shown in Fig. 5.16c, because analyzing the characteristic of TEG. The Fig. 5.16 shows the model after meshing in COMSOL.

![Model meshing in COMSOL.](image)

**Figure 5.16**: Model meshing in COMSOL.

### 5.5 Solver Studies and Study Types

In COMSOL, study define how to solve the problem, it is divided into three categories shown Tab. 5.1

<table>
<thead>
<tr>
<th>Node Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Study step</td>
<td>Determine overall settings suitable for a certain study type</td>
</tr>
<tr>
<td>Solver configuration</td>
<td>Contain the solvers and related configurations for dependent variables to solve for, intermediate storage of solutions, and specific solver settings</td>
</tr>
<tr>
<td>Job configuration</td>
<td>Contain all jobs defined for a study</td>
</tr>
</tbody>
</table>

In the thesis work, the stationary study step is used for thermal energy harvester model. It is used for field variable does not change with time.
6 Results

In this chapter the results of the thesis will be presented, along with explanations of the tests that were performed if needed.

6.1 Characteristic of TEG

This section shows the influence of air flow speed and temperature difference on TEG output performance.

6.1.1 Output power of TEG as a function of $v_{\text{Air}}$

In Fig. 6.1, for peltier element, when the air flow speed increases, the output power of TEG increases at the same temperature gradient. For example, at $\Delta T_s = 30 \degree C$, when $v_{\text{Air}} = 0.4 \, m/s$, the maximum output power is $425.51 \, \mu W$, when $v_{\text{Air}} = 0.6 \, m/s$, the maximum output power is $817.32 \, \mu W$. The temperature gradient higher, the growth trend of output power is more obvious.

![Figure 6.1: $v_{\text{Air}}$ - $P_{\text{max}}$ curve with $R_L = 1.6 \, \Omega$.](image)

---

0 5 10 15 20 25 30

Temperature Differences/degC

0 100 200 300 400 500 600 700 800 900

Power/\mu W

No heatsink $P&\Delta T_s$ curve

- $v_{\text{Air}}=0.1$
- $v_{\text{Air}}=0.2$
- $v_{\text{Air}}=0.4$
- $v_{\text{Air}}=0.6$

---
6. Results

Cooling air flow removes heat from TEG surface. Adding proper air flow speed can improve the output performance of TEG at high temperature gradient.

6.1.2 Output power of TEG as a function of $\Delta T_s$

In Fig. 6.2, for the peltier element, when temperature difference increases, the output power of is increases at the same constant air flow speed. For example, at $v_{Air} = 0.6 \ m/s$, when $\Delta T_s = 25 \ ^\circ C$, the maximum output power is 577.39 $\mu W$, when $\Delta T_s = 30 \ ^\circ C$, the maximum output power is 817.32 $\mu W$. As the air flow speed increased, the growth trend of output power is more obvious.

![Figure 6.2: $\Delta T_s - P_{max}$ curve with $R_L = 1.6 \ \Omega$.](image)

6.2 Cooling down performance of Heat sink

There are many factors can affect the cooling down performance. In this thesis, different materials, different structures, and different air flow directions have been studied.

6.2.1 Material of heat sink

The difference between $\Delta T_{Cu}$ and $\Delta T_{Al}$ of three different heat sinks is calculated to compare which material is better, in Fig. 6.3, the copper heat sinks have almost negligible better performance than alumina heat sinks.
Figure 6.3: $v_{\text{Air}}$ - Difference of three different heat sinks.
In order to study how much TEG output performance can be improved by using different materials, the ratio needs to be calculated. It is calculated by $\frac{\Delta T_{Cu}}{\Delta T_{Al}}$ of three different heat sinks, in Fig. 6.4, the copper heat sinks have almost negligible better performance than alumina heat sinks, it has been improved by 4%.
Figure 6.4: $v_{\text{Air}}$-Ratio of three different heat sinks.
6. Results

6.2.2 Structure of Heat sink

It can be seen in Fig. 6.5, when air flow speed is at lower speed, the square fin heat sink has better cooling down performance than angled fin and pin fin heat sink, as the air flow speed increased, the square angled fin heat sink has better cooling down performance than squared fin and pin fin.
6. Results

6.2.3 The influence of air flow direction on heat sink

It can be seen in Fig. 6.6, for square angled fin heat sink and squared fin heat sink, when the air flow direction changes, the output power of TEG is changed in the big range. Hence the different air flow directions has a great influence on square angled fin heat sink and squared fin heat sink. For pin fin heat sink, when the air flow direction changes, the output power of TEG is changed in the small range. Hence the different air flow directions has a negligible influence on pin fin heat sink.

\[
\text{Influence of air flow direction on heat sink (v_{Air}=0.1 & T_s=30)}
\]

\[
\text{Influence of air flow direction on heat sink (v_{Air}=0.2 & T_s=30)}
\]

\[
\text{Influence of air flow direction on heat sink (v_{Air}=0.4 & T_s=30)}
\]

\[
\text{Influence of air flow direction on heat sink (v_{Air}=0.6 & T_s=30)}
\]

**Figure 6.6:** The \( P_{\text{out}} \) of different air flow directions for heat sinks.

The average output power \( P_{\text{out}} \), which is calculated by \( \frac{1}{3}(P_{0\deg} + P_{45\deg} + P_{90\deg}) \), of different air flow directions for heat sinks are listed in Tab. 6.1. If the air flow direction is unknown and it changes all the time, when the air flow is at lower speed, the squared fin heat sink has better cooling down performance than angled fin heat sink and pin fin heat sink, when the air flow speed increase, the pin fin heat sink has better cooling down performance than angled fin heat sink and squared fin heat sink.
Table 6.1: The $P_{\text{out}}$ of different air flow directions for heat sinks.

<table>
<thead>
<tr>
<th>$v_{\text{Air}} \text{ m/s}$</th>
<th>Heat Sink</th>
<th>Angled Fin</th>
<th>Squared Fin</th>
<th>Pin Fin</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td></td>
<td>1853.9</td>
<td>1921.7</td>
<td>1787.5</td>
</tr>
<tr>
<td>0.2</td>
<td></td>
<td>5389.3</td>
<td>5250.8</td>
<td>5336.1</td>
</tr>
<tr>
<td>0.4</td>
<td></td>
<td>15391.7</td>
<td>14313.7</td>
<td>15978.7</td>
</tr>
<tr>
<td>0.6</td>
<td></td>
<td>25947.3</td>
<td>24135</td>
<td>27706</td>
</tr>
</tbody>
</table>

The output power of TEG with different heat sinks in 0° direction is as reference to study the influence of the unknown air flow direction and the direction is constant. Tab. 6.2 lists output power dissipation ratio when the air flow direction changes from 0° to 45° and from 0° to 90°. The output power dissipation is calculated by $\frac{P_{\text{ref}} - P_{\text{changed}}}{P_{\text{ref}}}$. If the air flow direction is unknown and the direction is constant, the pin fin heat sink has better cooling down performance than angled fin heat sink and squared fin heat sink.

Table 6.2: How much percent of $P_{\text{out}}$ lost when the air flow directions changed.

<table>
<thead>
<tr>
<th>Ratio $v_{\text{Air}} \text{ m/s}$</th>
<th>Heat Sink</th>
<th>Angled Fin</th>
<th>Squared Fin</th>
<th>Pin Fin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0° → 45°</td>
<td>0° → 90°</td>
<td>0° → 45°</td>
</tr>
<tr>
<td>0.1 m/s</td>
<td></td>
<td>41.09%</td>
<td>37.46%</td>
<td>54.03%</td>
</tr>
<tr>
<td>0.2 m/s</td>
<td></td>
<td>54.48%</td>
<td>43.72%</td>
<td>46.58%</td>
</tr>
<tr>
<td>0.4 m/s</td>
<td></td>
<td>58.88%</td>
<td>41.53%</td>
<td>34.05%</td>
</tr>
<tr>
<td>0.6 m/s</td>
<td></td>
<td>56.86%</td>
<td>36.67%</td>
<td>27.60%</td>
</tr>
</tbody>
</table>

6.3 Pin fin heat sink study

Fig. 6.7a and Fig. 6.7c show the influence of air flow on the 64 pin fin heat sink in COMSOL simulation. Fig. 6.7b and Fig. 6.7d show the influence of air flow on the 100 pin fin heat sink in COMSOL simulation. According to Bernoulli’s principle [44], as the speed of fluid increased, the pressure decreases. The maximum pressure of 64 pin fin heat sink is 3.82 Pa, the maximum pressure of 100 pin fin heat sink is 4.48 Pa, and comparing the maximum pressure, decreasing the number of pin can increase the air gap between two pins, it can improve the cooling down performance of pin fin heat sink.
6. Results

(a) The pressure of air flow for 64 pin fin heat sink in COMSOL.

(b) The pressure of air flow for 100 pin fin heat sink in COMSOL.

(c) The velocity of air flow for 64 pin fin heat sink in COMSOL.

(d) The velocity of air flow for 100 pin fin heat sink in COMSOL.

**Figure 6.7:** The different numbers of pin fin heat sinks in COMSOL

It can be seen in Fig. 6.8, using the same size of each pin in the same area, properly increasing air gap between two pins can improve cooling down performance by 30%.
Figure 6.8: $\Delta T_s - P_{out}$ at different air flow speed.
Summary and Conclusion

Nowadays, wireless sensor network is more and more widely in our daily life. As everyone knows, the most common way to power wireless sensors is to use battery. However, the battery has limited of their lifetime. So that to to solve the problem of battery which are powered to WSN nodes becomes more and more pivotal. To add an energy harvester is a good way to extend the lifetime of WSN nodes efficiently.

7.1 Thesis conclusions

The thesis work studies the characteristic of TEG and the influence of heat sink on TEG in indoor condition by using COMSOL. The conclusions are listed below.

- Temperature difference, which is between peltier element hot side and cold side, is one factor to affect output performance of TEG. Higher temperature difference can collect more power. If the air flow is 0.1 m/s and without using heat sink, when the air temperature is 20 °C, and the hot side temperature of the peltier element is 25 °C, the output power is 2.3701 µW. When the hot side temperature of the peltier element increases to 50 °C, the output power is 81.845 µW.

- Air flow velocity is another factor that affect output performance of TEG. Higher air flow velocity can remove more heat from device, it will have a big influence especially at large temperature difference. If the temperature difference, which is between air temperature and peltier element hot side temperature, is 5 °C and without using heat sink, when the air flow speed is 0.1 m/s, the output power is 2.3701 µW. When the air flow speed increases to 0.6 m/s, the output power is 28.034 µW.

- Heat sink can cool down the cold side of TEG in order to obtain bigger temperature difference between its two sides. The cooling down performance of heat sink depends on its structure and material, air flow speed and directions. Comparing the different structures of heat sinks, when the air flow speed is 0.6 m/s and the temperature difference between air temperature and peltier element hot side temperature is 30 °C, the output power of using pin fin heat sink is 30443 µW, the output power of using square angled fin heat sink is 37701 µW, the output power of using squared fin heat sink is 29949 µW. The square angled fin heat sink has better cooling down performance than squared fin, because the top surface of square angled fin is larger, that means the contact area with ambient air flow is larger. The structure of pin fin heat sink is more complex, the size of each pin top area and the distance between two
pins both can affect cooling down performance. With the same size of pin in the same area, properly increasing air gap between two pins can improve cooling down performance, it has been obvious that it can be improved by 30%. There are two materials that commonly used of heat sink, copper and alumina. Comparing these two materials, copper has higher thermal conductivity and more efficient heat absorption, however, copper heat sinks have almost negligible better performance than alumina heat sinks, the improvement has been obvious by 4%. The air flow direction also can affect the cooling down performance of heat sink. For squared fin and square angled fin heat sink, it has a great influence, but for pin fin heat sink, it has a negligible influence. If the air flow direction is unknown and it changes all the time, when the air flow speed is low, the squared fin heat sink has better cooling down performance, as the air flow speed increased, the pin fin heat sink has better cooling down performance. If the air flow direction is unknown and the direction is constant, the pin fin heat sink has better cooling down performance than square angled fin heat sink and squared fin heat sink.

- The data collected in COMSOL simulation differs significantly from experimental setup results [45]. The cause for differences could be modeling of peltier element, non uniform air flow and inaccuracy in the temperature measurements where only one single point of the surface of peltier element area to be measured, not the entire area.

### 7.2 Discussion of Contributions

This kind of thermal energy harvesting system is easy to manufacture and implement. It also can be available in any applications or environment with the small temperature difference existence. When the thermal energy harvesting system is used, there is no pollution of the surrounding environment, including devices and human being. Compared to the situation of battery-operated devices and the potential pollution when a large number of devices are deployed in the environment. Thereby, the thermal energy harvesting system is friendly to use.

### 7.3 Future Work

- Investigate the reasons for difference in simulation results and experimental results.
- Apply the modeling, methods used in this thesis to optimize heat sink designs.
Bibliography


[42] “Glacialtech announces igloo fs125s 30w cold forged pin fin heatsink,” Eco-Business, Jan 2016.

