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A Cooling Method Based on Thermoelectric Effect - Peltier Cooling System

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Abstract. **Energy consumption throughout the world has been increasing in recent years and is a major concern due to its effect on climate change. According to NASA, climate change has led to stronger hurricanes, more droughts and heat waves, sea level rise, and a prediction that the arctic will be ice-free by mid-century. One of the most notable energy consumption methods, which negatively affect the climate, is the heating and cooling of buildings. As a result, minimizing the need for energy use in buildings for heating and cooling application is a widely explored field of research. While energy efficiency has drastically improved in recent years, the use of harmful refrigerants, such as R-410a, has already taken a huge toll on the environment. This presented a need for the cooling and heating of buildings without the use of harmful refrigerants. An alternative method of refrigeration is the use of Thermoelectric Modules (TEMs) due to their nature of having no mechanical moving parts, being highly reliable, compact in size, light in weight, requiring no working fluid, and most importantly: require no use of refrigerants. Our project aims to design and create a fully functioning system which uses TEMs as an alternative for cooling and heating of common spaces.**

Key words：Thermoelectric effect, cooling system, energy.

I. Introduction

A thermoelectric based cooling system is introduced in this section. First, there is an outline of the problem statement, which describes the problem for which the thermoelectric based cooling system will be a solution. The motivation behind the system is then indicated, and the requirements for the system outlined. Finally, the global, social, and contemporary impacts of the cooling system compared to other HVAC systems are discussed.

A. Problem Statement

Energy consumption in building sectors has increased dramatically within the last decade due to worldwide population growth. Because of that, more people spend their time indoor, elevating the demand for optimal and more efficient cooling and heating systems to provide thermal comfort. This report proposes a thermoelectric-based system for building cooling and heating applications. The system will consist of Thermoelectric Modules (TEMs) embedded into the ceiling envelope of the proposed test building environment, which will provide cooling and heating through radiation and convection. The project will adhere to the ASHRAE 55 thermal comfort standards. The final product will be utilized for educational purposes in the Heat Transfer laboratory at the Florida Institute of Technology for teaching principles of radiative cooling and heating, as well as the Peltier effect.

B. Motivation

Climate change has been a major growing concern in recent years, with its main contributor being Greenhouse Gas (GHG) emissions. Researches and studies are attempting to further identify sources of GHGs, and pinpoint ways to reduce their emissions. According to the US Energy Information Administration (EIA), energy usage in building sector accounts for 20% of global energy consumption. In 2018, 40% of the energy consumed in the United States came from buildings, which is equivalent to 40 Quadrillion British Thermal Units (BTU). Additionally, cooling and heating alone account for over half of the total energy consumption in buildings [1].

Refrigerants are a commonly used substance for refrigeration. These can vary from Chlorofluorocarbons (CFCs), Hydrochlorofluorocarbons (HCFCs), and Hydrofluorocarbons (HFCs), all of which pose a threat to the environment in numerous ways. The United States Environmental Protection Agency (EPA) has categorized these harmful chemicals regarding their Ozone Depletion Potential (ODP) and their Global Warming Potential (GWP). ODPs are used to understand the different impact gases have on the ozone through a numerical ranking system where a higher number indicates a more damaging effect on the environment. GWP is used to determine the strength of a gas' greenhouse effect; the higher the GWP, the warmer earth will get with an equal amount of CO_2. Some of these harmful refrigerants have reached values of over 14,000 for their GWP and 16 for their ODP [2]. The EIA also states that, in the past eight years, emissions due to refrigerants have more than tripled as a result of a dependence on R-410 in air conditioners.

Because of the negative effects refrigerants have on the environment as well as on humans, there is a great necessity to find alternatives for cooling and heating systems, as they pose one of the greatest threats to the environment and future welfare. Consequently, the need for innovative building cooling and heating that doesn't rely on these harmful refrigerants will improve both energy efficiency and environmental concerns by doing so.

Thermoelectric Modules (TEMs) have recently become a growing topic in research due to their ability to convert Direct

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Current (DC) power into a temperature gradient. The feasibility to utilize TEMs as an alternative to conventional vapor compression Heating Ventilation Air Conditioning and Refrigeration (HVAC&R) systems will eliminate the harmful effects of refrigerants as well as reduce overall energy consumption.

C. Global, Social, and Contemporary Impact

Conventional HVAC systems pose a significant threat to the environment by dumping harmful chemicals into the atmosphere using refrigerants. They also consume an enormous amount of energy, which puts a strain on the electricity generation industry, leading to more GHG emissions. Most of the AC units in use today still make use of refrigerants, such as R-134a, which have adverse effects on the environment. Several debates have been addressing the prohibition of these GHGs to avoid the greenhouse effect itself, as well as the depletion of the ozone layer.

With that in mind, the system proposed in this report consists of a fully controlled environment, providing heating and cooling while still being energy efficient. The project makes use of TEMs to provide cooling and heating through radiation and convection. Thermoelectric technology is seen as one of the most attractive direct power generation techniques used to recover wasted heat energy because of the direct conversion from thermal energy to electrical energy [3].

Another benefit this novel cooling system can offer, is the ability to precisely narrow down where the customer wants the cooling or heating process to happen. Consider a classroom with a professor and a couple of students only. With a sophisticated control system, the thermoelectric modules can provide cooling or heating to the desired area where the occupants are located, saving energy and providing thermal comfort almost instantly due to its high controllability. This simple example, when analyzed, demonstrates the potential to control the temperature in different areas of the same room, which is not possible in any HVAC system nowadays, targeting specific customers in need of this controllability. Besides that, the thermoelectric modules allow an excellent precision in temperature, assuring accurate thermal comfort conditions.

II. Recommended Solution

This chapter begins with the proposed design of the system—what would be done for the cooling system to operate optimally. The antecedent section is on solution principles, which entails the considerations, and the criteria used for selection of the different aspects of the system. Theoretical analyses are also included in this chapter; this includes COP, and FMEA. The chapter concludes with decision matrices, bill of material and a description of the assembly of the system

A. Materials and Methods

Section A presents the review of the research analyzed during the semester, where it is divided into subsections that consist of the significant design aspects regarding the project. The first design aspect presented is energy efficiency, where thermoelectric modules, coefficient of performance (COP), and heat sinks are explained thoroughly. Next, thermal comfort aspect is discussed, where requirements stipulated by ASHRAE are analyzed and studied to be applied to the final project. The last element presented is the product design, where the choice of materials and components are explored based on research conduct over the past years regarding radiant cooling systems.

1)Energy Efficiency. Energy efficiency is arguably one of the most important aspects considered in creating and designing cooling systems. The main concern with using thermoelectric modules for building cooling and heating applications is their low efficiency. If the proposed design can maintain a low DT, then the efficiency will reach its maximum, therefore making it a viable option for the future of the HVAC&R Industry. The Energy Efficiency section consists of two areas, the Thermoelectric Modules (TEMs) and the Heat Sink Design. Research was conducted in both areas to decide which would be the most efficient design and configuration for the system.

a)Thermoelectric Modules. Solid State cooling is made up of various effects which make use of groundbreaking means to provide cooling to a system. These effects ranges from electron tunneling to the magnetocaloric effect, thermoelastic effect, and the Peltier effect. The Peltier effect is the only effect that has been commercialized as the others are still under research. The Peltier effect states that, when current (Direct Current) goes into a Peltier device, the phenomenon of the absorption of heat by a junction between two different material occurs. It is due to this phenomenon that one side of the device cools down (absorbs thermal energy) and the other heats up (rejects thermal energy) [4].

Peltier devices, also known as Thermoelectric Modules (TEMs), are devices that effectively transfer heat along with an array of pellets in the module to make one side hot and the other cold for various applications. The basic build of a TE module consists of P and N-type semiconductors, typically made up of Bismuth Telluride material to effectively transfer heat. These elements are then placed in between two ceramic plates that are both ductile and strong thermal conductors.

To effectively apply the thermoelectric module for the system, prior knowledge of the components' performance is needed. Research Paper published by H.Y Zhang [5] looks into how to determine various properties of a TE module effectively, and with the information gathered, cooling power, coefficient of performance (COP), and the figure of merit (ZT) could be determined for the system to be built. The cooling power was a measurement of how much heat a TEM would need to remove from a system. The coefficient of performance (COP), which represents the efficiency of a refrigeration system, is the ratio of the cooling power provided by each module to the total input electrical power. It should be noted that the lower the COP value achieved by a system, the less efficient it will be, and with that, a tangible value of 1.5 was set. The Figure of Merit (ZT) is a term that balances the strength of the thermoelectric effect to the losses in the system and is directly related to COP, meaning that increasing ZT will increase COP as well. Based on the target value set for the COP, a determination of the number of TEMs needed for the system occurred, as well as the temperature of the hot side and cold side of the module. The calculations regarding these aspects were found on the paper co-written by Dr. Hamidreza Najafi in which an analysis of a hybrid system consisting of TE modules and PV panels were analyzed and tested.

b)Heat Sink Design. A heat sink is a device used to assist and increase the rate of heat transfer from a mechanism, such as, heat engines, heat pumps, or any equipment that requires heat dissipation. Another common way that heat sinks can be represented is that of a reservoir, where thermal energy that can hinder the operation of a device can be stored and then dissipated more efficiently.

Heat pipe heat sinks provide a high heat conductivity, transferring heat between two solid interfaces by applying the principles of thermal conductivity and phase transition. Heat pipes are constituted of an evaporator and a condenser where liquid inside evaporates at the hot interface by heat absorption, traveling to the cold interface along heat pipe where the vapor condenses back by releasing the heat. The optimum number of TEMs with heat pipe depends on the ambient temperature because when the heat fluxes decrease, the thermal resistances increase. Fewer TEMs are needed if the comfort temperature gets further. At a constant operative temperature, air volumetric flow affects the COP, and higher air volumetric flow leads to a higher COP value since the thermal resistance decrease with the increase of air volumetric flow.

Aranguren P. et al. tested the performance of the heat pipes for two orientations: vertical and horizontal. The result is different for the heat pipes placed on the hot side and the cold side. For the hot side of the TEM, the thermal resistance of the heat pipe does not change with its orientation, but for the cold side, the thermal resistance of the heat pipe is better in a vertical direction than in a horizontal orientation. However, the vertical position provides a higher COP than the horizontal position. In the summer, the difference can be up to 12% and a difference of 5% in winter.

As well as the orientation of the heat pipes, the arrangement and spacing of thermoelectric modules with heat pipes can affect the performance of the system. Numerical simulation models were developed and studied to find the most optimal configuration . Triangular and rectangular configurations were tested as well as configurations with a combination of both triangular and rectangular. The results gathered showed that the average temperature differences are $3.1 \pm 0.23°K$ and $3.4 \pm 0.41°K$ between the hot and cold spots in the plate for the triangular and rectangular configurations, respectively, proving that triangular configuration provides better performance. In addition to that, simulations were developed to investigate the effects of the spacings between the TEMs. The spacings vary from 0.28m to 0.38m with 0.02m interval. By observing a series of plots, the result shows that 0.28m for the spacing between the TEMs provides the lowest average temperature difference of $2.7 \pm 0.20°K$ between the hot and cold spots in the plate, which satisfies the recommendation for radiant cooling panel from ASHRAE. Therefore, triangular configuration with 0.28m spacing was proven to be the most viable option for a thermoelectric based system utilizing heat pipes.

2)Product Design. The product design section evaluates the research done for optimizing the efficiency of the system to be built. The major aspects studied were the possible materials to be used for the ceiling tile to maximize its performance and the hardware and software aspects involved in this project.

a)Ceiling Materials. When designing a radiant cooling system, the selection of materials to be used on the ceiling tile is important because it will determine how efficient the system will provide cooling to the environment. During the research, two commercially available types of ceiling configurations were analyzed to decide which one would be more suitable to the project, one metal, and one gypsum perforated with phase changing materials (PCM) incorporated into it.

Most radiant cooling systems utilize metal panels to transfer heat due to their high thermal conductivity. However, the metal panels do not maintain the desired operative temperature for a long time, which requires the system to be turned on several times throughout the day . The advantages of using metal panels are that they light, easy to maintain, and they also provide a fast transfer of heat from the source to the room. The other option analyzed, gypsum/PCM panels, offer the ability to store more heat per unit volume due to their latent heat thermal storage, and is easy to install and to maintain.

Researchers have been working on integrating the two configurations to optimize the efficiency of the system, combining the advantages of metal panels with PCM. A thermoelectric cooling-based system incorporating PCM can store cold thermal energy at night and functions as a heat sink to reduce the temperature of the hot side of the thermoelectric modules during daytime improving the overall thermal efficiency of the system. The combination of metal panels and PCM have shown that the improvement in system performance is significant, because the metal panels allow heat to be transferred fast to the environment, providing the necessary thermal comfort desired by the end-user. The PCM integrated into the ceiling helps insulate the room, preventing heat from being dissipated. Therefore, the combination of the two configurations allows the system to have a 56% improvement in COP, while reducing the need to be turned on several times throughout the day because the incorporated phase change materials keep the room insulated for a longer time, thus saving energy to the end-user .

b)Control System. The control system focuses on finding the most efficient way to control and power a Peltier based cooling system. The system comprises of a few major aspects: a power source (for power generation), a TEC controller (for temperature control of the TE modules), a raspberry pi (for system functionality and app accessibility), and the sensors (for testing and better control the system). The system would also contain a Thermoelectric Generator (TEG) to use the dissipated heat to power a LED, to show that the Seebeck effect can also be used to increase the energy efficiency and conservation of energy of the system. This configuration would also affect the efficiency of the entire system.

The selection of a TEC controller was based on the fact that it's very efficient and the advantages outweigh the disadvantages. The TEC controller is essential for safety precautions; parameters can be set and monitored to ensure that the system doesn't fail. These parameters include; maximum voltage, maximum current, TE module temperature, and TEC controller shut-down temperature. The TEC controller also proves to be most efficient, as it is reliable and reduces costs related to power generation. There is minimum power loss due to less heat generation, less power consumption, lower operating temperature, and minimal heat sink usage .

The configuration of the TE modules have also been proven to affect the efficiency of the system; studies show that an increase in COP happens with a series configuration; the COP increases as more TE modules are added. However, parallel will be the safest configuration if TE module failure is considered; if one module fails, the others will continue to work. A balance between efficiency and functionality must be obtained, ensuring the best possible scenario.

c)Test Building Environment. Up to this point, the focus has been on the ceiling tile and its design. However, another essential factor to consider is the test building environment. The test building environment must meet the requirements to have an energy-efficient system. When looking at it, the research was split into several characteristics that must be addressed. These characteristics include size, materials, and shape of the area where the system will be tested. A decision was made to have a box shape for the environment in order to replicate an actual room.

When looking for materials to use, several options were evaluated. Various drawbacks and advantages of each option were analyzed. One of the materials evaluated was plywood, which is lightweight, and widely utilized in small scale room applications. This material can be seen in dollhouses, as well as residential applications. One of the advantages of this material was the light weight compared to the other materials considered. However, the design of the system must be as energy efficient as possible. Plywood having a low R-value wasn't the best option. Another option was sheetrock which is a lightweight drywall that weighs 30% less than regular drywall. This was evaluated due to its common usage for residential applications. The R-value for this material was better compared to plywood, but it was still very low for the goals and requirements set for the design.

Finally, in order to create an energy efficient environment, the Structural Insulated Panels (SIPs) were studied. SIPs are a high-performance building system for residential, and commercial applications. These panels provide an extremely strong, energy efficient, and cost-effective system. The R-value of the specific type of SIPs being used is R-12.

B. Final Design

The final design is meant to show the effects of radiative cooling in a building environment. To emulate this effect, a ceiling tile was constructed with thermoelectric modules attached on one side. On the thermoelectric modules, there are heat sinks to dissipate the thermal energy. The TEMs are connected to a power source as well as the heat sinks –for the fans. Figure 1 below shows the enclosure which demonstrate the effects of radiative cooling. The building environment itself will has an opening with glass that can be moved so people or objects can be placed inside and tests can be conducted to determine how effective the system is, as well as finding ways to optimize it. The apparatus will also have wheels so it can be easily transportable for further testing, such as in an outdoor vs indoor environment. Another component that had to be design by itself was the ventilation system, which serves two purposes. One is to redirect cooling air from the test environment to aid in an effective heat transfer. Two is redirect the heat transferred to the thermoelectric generator to recover some energy form the waste heat to be used to increase the efficiency of the system.

Figure 1. Complete Design of Apparatus.

C. Patents Search

The project is unique and will theoretically revolutionize the HVAC&R industry. Thus, researches need to be conducted on patents to verify that the apparatus is entirely new and state of the art, as well as potentially check if the idea has already been established on a technical level. If the search determines that there are no current patents which utilize the same principles, then it may be a possibility to patent the idea.

When doing the patent search on Google Patents, the search came across four specific patents that resemble the planned design. Alexander Gurevich et al.filed a patent for a thermoelectric air conditioner designed for a temperature control of a confined space. This patent is similar in the sense that the design incorporates heat sinks, temperature controls, and phase change materials. This is different from our unit because we will have the thermoelectric modules incorporated into the building envelop as opposed to a separate unit. Two more patents utilize the same air conditioning unit principle but on a more basic level with different configurations. The last patent which resembles the proposed design and intent more so, was created by Lon E. Bell. This patent seems to be focused on cooling down or heating up a working fluid to be transported for cooling and heating purposes using radiative heat transfer from thermoelectric modules.

All of these patents relate to thermoelectric cooling and heating apparatus, and there are several more dealing specifically with cooling and heating. However, the majority of them are for vehicle applications. There have been inclusions of the use of working fluids as well as incorporation of PCMs in these patents. Any and all patent works for a thermoelectric radiant cooling and or heating for building applications are yet to be established.

III. Future Work

Future work entail the selections made for different aspects of the thermoelectric based cooling system, as well as the considerations and criteria used to make the decisions. These aspects include: the thermoelectric modules, the heat sinks, the ceiling configuration and the test building environment.

Further, possible additions and improvements that can be made to the project will be addressed and the description of four new experiments for the heat transfer laboratory will be presented. Since this project has an educational purpose, there will be a section dedicated for each experiment explaining the objectives and fundamental that will be taught. Finally, the experimental data will be sorted out and analyzed and a discussion on a conference paper will be addressed.

IV. Conclusion

Future work will focus on thermoelectric modules, radiators, ceiling configurations and testing of the building environment for standard measurements and considerations, and on the selection of different aspects of thermoelectric based cooling systems, with the aim of improving the system

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