Design and Development Heat Dissipation Systems for Thermoelectric Coolers

Abdelrahim Zidan[1] and Basem Badr[2*]
[1]Undergraduate Student at Mechatronics Engineering Dep., College of Engineering, 6th of October University, Giza, Egypt
[2*]CTO at Lotus Power, Vancouver, BC, Canada
Email: [1]abdelrahimzidan.study@gmail and [2*]bbadr.digital@gmail.com

***Abstract*— Air conditioner (AC) systems present a big challenge for the environment because of the electricity demand. This paper investigates AC system designs to meet the environmental requirement of less power demand and improving efficiency. In this work, a novel heat dissipation system is designed and built to enhance the efficacy of the thermoelectric cooler (TEC) AC systems. The new heat dissipation system is based on liquid-cooling system, where a new water block is designed to make a direct connection between the hot side of the TEC and the coolant (water) by integrating the hot side of the TEC module into the water block. The system performance of this novel water-cooling system is compared and analyzed with the traditional cooling systems that are air-cooling and liquid-cooling systems. Experiments and different test profiles are conducted to analyze the system performance of the traditional and novel cooling systems with respect to power consumption, efficiency, and output response specifications. The experimental results indicate that the coefficient of performance (CoP) of the novel heat dissipation system is higher than the CoP of the traditional air-cooling and the traditional liquid-cooling system systems by 44.7% and 26.3%, respectively. The traditional liquid-cooling system consumes the highest electric power in comparison to the air-cooling system and novel liquid-cooling system. The largest temperate difference is achieved using the novel cooling system with respect to the same ambient temperature.**

Keywords*— *Thermoelectric Coolers, Coefficient of Performance, Thermoelectric Air Conditioners, TEC Heat Dissipation System

I. INTRODUCTION

Air conditioning (AC) is the most used to cool indoor spaces. Although, it contributes to a substantial rise in global electricity demand, currently estimated at one trillion kilowatt-hours (kWh) annually. Projections suggest this could escalate to over 10,000 TWh by 2100. The electricity used for AC is primarily generated from fossil fuels, leading to significant carbon dioxide (CO_2) emissions that exacerbate climate change. Additionally, refrigerants used in AC systems can have high global warming potential, further contributing to greenhouse gas emissions [1]. Thermoelectric coolers (TECs) are increasingly recognized as a viable alternative to traditional AC systems, particularly in applications where compactness, quiet operation, and environmental sustainability are paramount. Unlike conventional AC units, which rely on refrigerants and mechanical compressors, TECs utilize the Peltier effect to create a temperature difference, allowing for efficient cooling without moving parts. This results in a system that operates silently and has a smaller footprint, making it ideal for applications such as personal cooling, portable refrigeration, and electronic device cooling. Despite these advantages, TECs face significant limitations, particularly in terms of their efficiency. The low coefficient of performance (CoP) of TECs is primarily attributed to the thermoelectric materials used, which often exhibit suboptimal thermoelectric properties, as well as challenges related to heat dissipation from the hot side of the device. To overcome these limitations, ongoing research is focused on the development of advanced materials that can enhance the performance of TECs. For instance, nanostructured materials, superlattices, and composites are being explored for their potential to optimize the key thermoelectric properties which are the Seebeck coefficient, electrical conductivity, and thermal conductivity. By manipulating the microstructure of these materials, researchers aim to achieve higher figure of merit (ZT) values, which directly correlate with improved efficiency in thermoelectric devices. Additionally, computational modeling plays a crucial role in this research, enabling scientists to simulate and predict the behavior of new materials under various conditions [2].

This paper focuses on the design and development of a novel heat dissipation system to improve the efficiency of the AC. The proposed AC system is designed based on a water-cooling system, where different test profiles are conducted to analyze the system's performance. The proposed novel cooling system is evaluated in comparison to traditional cooling systems in the TEC AC systems. Figure 1 shows the block diagram of the novel cooling AC system, where the water block design makes a direct connection between the TEC hot side and the water or coolant which decreases the resistivity and enhances the performance.

This paper is structured as follows. Section I explains the impact of the AC systems on the environment. Section II shows the literature survey of the AC system. The design and development methodology of the novel AC cooling system is described in Section III. The experimental setup and validation are illustrated in Section IV. Experimental results and analysis are described in Section V. Finally, the conclusion and future works are drawn in Section VI.

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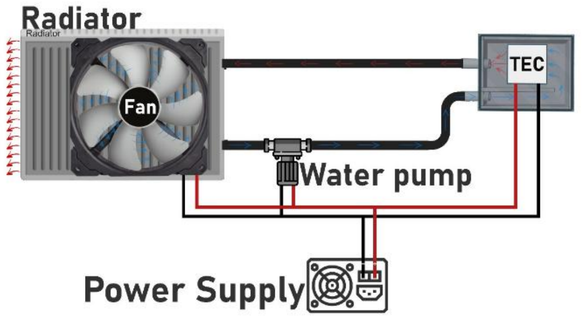

Figure 1: Block diagram of the novel cooling AC system

II. LITERATURE SURVEY

This section discusses the literature search on thermoelectric (TE) AC and heating, ventilation, and air conditioning (HVAC) systems, with a focus on advancements related to heat dissipation and efficiency improvement. This literature study provides hints and keynotes in the design and development of the proposed AC system.

Anthony A. Adeyanju, et al., designed and tested a prototype of the TE AC, where they did calculations with respect to the conditions of the AC system. The hot side's operating temperature was below the largest limit of 138°C and calculated the fan cubic feet per minute ratings, to find the proper fan. The test results found that the device was able to cool and dehumidify the air within the thermal comfort zone of 22°C and 53.7% relative humidity, respectively. The CoP of the system was 0.465, their AC design was cheaper than the tradition systems by 47.5% [3]. D. Astrain et al., explored advancements in TE refrigeration, aiming to improve the CoP through an enhanced heat dissipation system. They introduced a thermosyphon device that utilized phase change to optimize heat transfer and reduce thermal resistance. The device achieved a thermal resistance of 0.110 kW, representing a 36% improvement over conventional finned dissipaters. Experimental results showed that this innovation increased the CoP of thermoelectric refrigerators by up to 32% compared to traditional systems. The performance of the thermosyphon system can be influenced by ambient temperature it may adversely affect the efficiency of the phase change process, thereby limiting the overall performance of the thermosyphon [4]. Kashif Irshad, et al., investigated the performance of the TE AC system both under steady-state and pulse operations. They combined actions of the Peltier heat, cooling load, Fourier heat, and Joule heat, all of which operated simultaneously during steady state operation, and determined the optimum performance of the cold side temperature of the thermoelectric module (TEMs). During pulse operation, the peak overshot and minimum temperature of the cold side of TEMs increased as the experiment progressed for all cooling loads. Two factors contributed to the increase in peak overshoot and minimum temperature of the cold side of TEMs, which included the accumulation of Joule heat in the element of TEMs and the increasing Fourier heat conduction in the element of TEMs. They observed that the average cold side temperature increased as the pulse width decreased from 40 to 9 seconds, and low current width caused an abrupt increase in the TEM's cold side minimum and overshoot temperatures. The pulse operation of a TE AC system provided better performance for building thermal management when compared to steady-state operation [5]. Wen-Yi Chen, et al., discussed TECs and their potential applications in different industries, which were versatile technologies used for temperature control in various fields such as consumer electronics, communications, automobiles, aerospace, etc. Their research focused on developing high-performance, low-cost, eco-friendly TECs. They highlighted challenges in TEC development, including optimization of material properties, considering various design parameters, and improving heat dissipation. The heat dissipation at both the cold and hot sides of TECs was particularly critical, as poor heat transfer performance could significantly reduce cooling capacity. They recommended exploring advanced materials, designing better heat sinks, improving TEC structures, and expanding their applications in the future outlook [2]. S. B. Riffat, et al., provided a comprehensive review of the present and potential applications of TE devices. They discussed the challenges associated with TE technology and highlighted research and development (R&D) efforts aimed at improving the performance and cost-effectiveness of TE devices. Various strategies for improving the performance and cost-effectiveness of TE devices were identified, which included optimizing the TE materials, and device design, improving thermal management, and reducing material and production costs. The authors also discussed potential applications of TE devices in various industries, including automotive, aerospace, and energy conversion. The energy costs and environmental regulations regarding the manufacture and release of CFCs (chlorofluorocarbon) have revived interest in this area and the need for continued R&D to overcome the challenges associated with TE technology and realize its potential for a wide range of applications [6]. Riffat, et al., examined strategies to improve the CoP of thermoelectric cooling systems and highlighted key areas that needed enhancement, which are points materials, CoP improvement, electric pulses, and multi-thermoelectric modules. The materials were based on Bismuth telluride (Bi2Te3) that were the leading low-temperature thermoelectric material with a maximum ZT value of around 1, but higher CoP values of 2 or 3 are desired to compete with vapor compression systems. They focused on reducing thermal conductivity through microstructure optimization and increased phonon scattering. Quasicrystals with a ZT exceeding 1 and thin-film thermoelectric materials offered promising avenues for achieving higher CoP, particularly by controlling phonon and electron transport in superlattices. Notably, thin film TEs have shown significant ZT enhancements at 300 K compared to bulk Bi2Te3 alloys and are commonly used for electronic device cooling. The CoP improvements were executed with respect to enhancing heat dissipation which was achieved by raising the cold side temperature and lowering the hot side temperature. Efficient heat exchangers with low thermal resistance contributed to CoP improvement. Increasing the number of thermoelectric modules reduced the heat load on each module, decreased heat flux densities, and enabled lower hot side temperatures. The electric pulses affected TECs, where the improvements were short-lived and had limited effectiveness. They recommended further research to understand the fundamental differences between Peltier and

Joule heat with respect to the electric pulses. Employing multistage thermoelectric modules significantly enhanced cooling system performance and CoP. Cascaded modules exhibited notable CoP improvements, especially at higher temperatures and enhanced cooling efficiency even at low temperatures. Location optimization of modules and temperature staging was critical for maximizing system efficiency [7]. Tamer Guclu, et al. provided a comprehensive evaluation of TECs in terms of type, material, design, modeling, thermal performance, potential applications, and economic/environmental aspects. The study highlighted the importance of temperature difference (ΔT) in determining CoP, maximum CoP was achieved when ΔT was close to zero. The study indicated that TECs offered reliable energy conversion without noise or vibration, and their CoP range has been improved. They integrated the TECs with phase change materials or water-cooling units, which enhanced the CoP by over 55%. They used pyramid-type multi-stage TECs with high conductance materials, which showed better cooling power than conventional single-stage TECs. Material type significantly affected the ZT value, whereas Cu1.94Se0.5S0.5 thermoelectric materials reached a maximum ZT of 2.3 [8]. A. E. Kabeel, et al., investigated and examined the impact of different operational parameters on the performance of a TE cooling system. The study parameters included input power, working fluid velocity, TEC module arrangement, and fluid type. The geometry was modeled using ANSYS software with two attached horizontal ducts and three thermoelectric modules. Simulation results showed that the overall CoP of the TE cooling system was increased when the applied input power was up to 8 W. It decreased when the input power was up to 18 W. Then, it took nearly a constant value, a noticeable enhancement in the CoP was found when the three TECs were in use and using pure water and nanofluid with 0.05% of nanoparticles as coolants took the maximum value [9]. Gaoju Xia et al., provided the cooling performance of TE refrigeration systems by designing a new finned heat sink. Experimental tests were conducted to evaluate the system's performance under various conditions, measuring parameters such as cooling airflow speed, TEC temperatures, and fan power consumption. The test results demonstrated that the new finned heat sink enhances the system's CoP by 22.8% and reduces thermal resistance by 42.6%. Furthermore, increasing the airflow speed contributed to lower cold side temperatures, with a minimum temperature of -8.25 °C achieved; although, the fan power consumption was higher than that of conventional fin heat sink refrigeration devices by 166% [10]. Alexandru, et al., conducted a comprehensive study on solar TE cooling systems and discussed TE cooling parameters and performance indicators. Their focus was primarily on the recent advancements in materials, modeling, and design approaches related to TE cooling systems. They highlighted the significance of the materials ZT, identifying (BiSb)2Te3 as the material with the highest ZT value of 3.3. Furthermore, they explored the potential use of solar TE cooling technologies in "nearly zero" energy buildings, as they emphasized the advantages of TE cooling devices. This was including their compact size, lightweight nature, high reliability, absence of mechanical moving parts, and working fluid. They utilized the direct current power source (without inverter) and the ease of switching between cooling and heating modes [11].

The following section describes the methodology of the proposed novel cooling AC system. The design and development of the proposed AC system are evaluated and compared with respect to the AC system in the literature survey, as described in Section V.

III. Methodology

This section elucidates the methodology and structure of an innovative cooling system employed to enhance the CoP in TE ACs. Currently available TE ACs utilize air-cooling or water-cooling systems to dissipate heat from the hot side of the TEC module. In the air-cooling system heatsinks and fans are attached to the TEC module's hot side and the thermal paste is applied between the TEC and the heatsink to fill microscopic gaps and uneven surfaces to optimize thermal conductivity and promote efficient heat dissipation. The limitations of the air-cooling system are complex structure, many items, and low flexibility, due to the direct attachment of heat sinks and fans to the TEC. The air-cooling systems combine the hot and cold sides of the TE AC within a single unit, this results in restricting its placement exclusively to windows. Consequently, relocating the TE AC becomes a challenging endeavor. On the other hand, water-cooling systems involve connecting the TEC module's hot side to a water block via a water pump. This pump circulates water to a radiator equipped with a fan, this system also employs thermal paste between the TEC and the water block. While the water-cooling systems effectively address the flexibility concern by allowing the separation and space of the indoor and outdoor units of the AC. Its drawback is using multiple thermal transfer materials (water and thermal paste) that leads to low reliability. The thermal paste in air-cooling and water-cooling systems require replacement often because of the change in thermal resistance [3-8].

The novel heat dissipation system is based on developing the traditional liquid-cooling system that is already in use in the TE ACs. The new water block is built to make a direct connection between the hot side of the TEC and the water or coolant. The design and the methodology of the system development ensure that the hot side of the TEC module integrates into a water block by using the innovative design of the water block and the TEC module. A water pump is used to circulate the coolant to the radiator equipped with a fan to dissipate its temperature. Thus, the problem of flexibility is solved by separating the indoor unit (cold side) from the outdoor unit (hot side) of the AC, and the problem of low efficiency is solved by using the new water block that makes a direct connection between the hot side of the TEC and the water or coolant. Figure 2 illustrates the water block diagram of the proposed TE AC system design, where a gasket is used to seal the TEC and the system from the liquid (water). The following sections describe the experimental setup and test results of the proposed system.

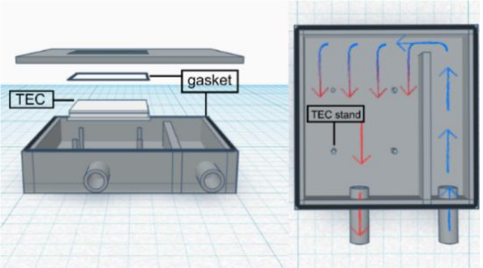

Figure 2: System overview of the proposed novel water-cooling system.

IV. System Setup

This section illustrates the system and experimental setups for verification and validation of the proposed novel liquid-cooling system. A comparative study of the three systems is conducted to analyze the system's performance, which are air-cooling, traditional liquid-cooling, and the new proposed liquid-cooling systems. Water is used in the liquid-cooling system, experiments are carried out over 20 minutes under a same ambient temperature condition of an average of 28.5 °C, to illustrate the system's performance between the proposed and the traditional cooling systems. All experiments are recorded, and the required measurements are to analyze the performance of the cooling systems. The equipment and instruments used in the measurements are DT-830D Mini Digital Multimeter, Arduino Uno, and two temperature sensors (DS18B20) to record and monitor the setup and temperature values. The Arduino Uno is programmed to stream the measurements live while experimenting. Figure 3 shows the flowchart implemented in the Arduino to detect the accurate temperature of these three cooling systems. This Arduino code sets up and reads from multiple DS18B20 temperature sensors with 12-bit resolution, ensuring accurate temperature measurements. It is well-suited for monitoring temperatures in systems experiments. The apparatus and materials used in the experiment are three units of TEC1-12706, a DC power supply (12V & 30A), an aluminum radiator, a water pump, a TE Peltier air cooling system kit, and thermally isolated tubes for liquid cooling systems. Figures 4-6 show the system setup using air-cooling, traditional liquid-cooling, and new liquid-cooling systems, respectively, where the common equipment and devices are used in the three setups with the different of the cooling system setups. For example, fan is used in the air-cooling system, as illustrated in Figure 4 and the proposed water block is used in the novel liquid-cooling system, as shown in Figure 6. The following section describes the experimental results and analysis.

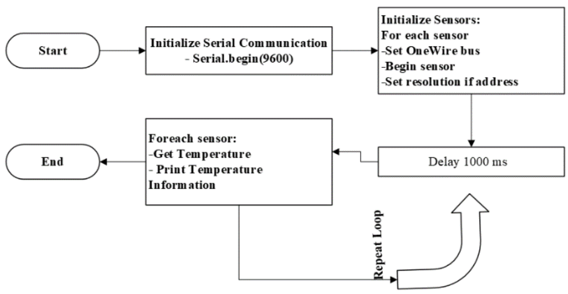

Figure 3: New cooling system setup

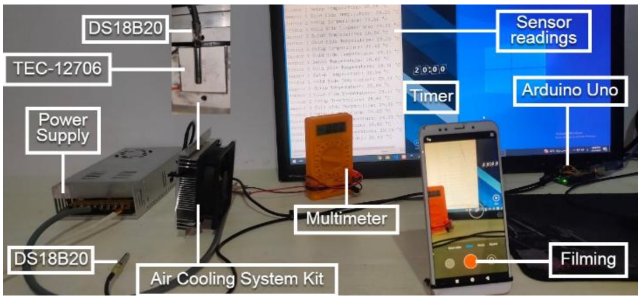

Figure 4: Air-cooling system setup

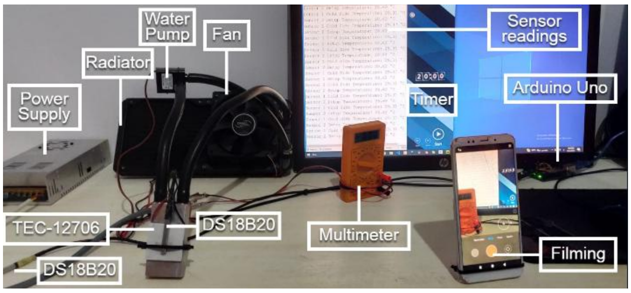

Figure 5: Liquid-cooling system setup

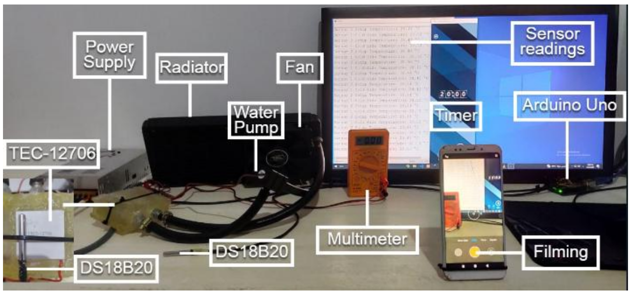

Figure 6: New cooling system setup

V. Results and Discussion

The three cooling systems (including traditional and new) are built, and different test profiles are conducted to analyze the system's performance. These cooling systems with the AC are installed in the same room dimension that is 3.1 x 3.1 x 2.8 m (width x length x height) and the temperature sensor is installed at the same location for all setups. The ambient temperature values and timestamp are logged and the power consumption are estimated to characterize the system performance. The ambient temperature is 28.25°C and quickly decreases to 0°C and -3.25°C (minimum value) in 123 and 316 seconds (about 2.05 and 5.3 minutes), respectively, from the start time when the new water-cooling system is used. The drawn current values of the new water-cooling system are 2.54A, 0.07A, and 0.27A for the TEC, the fan, and the water pump, respectively. The total power consumption value from the 12V power supply is 34.56 W. Although, the temperature decreases from 28.87°C to its minimum value of 5.69 °C in 1200 seconds (about 20 minutes) using the traditional air-cooling system. The drawn current values of the air-cooling system are 2.5 A and 0.12 A for the TEC and the fan, respectively. The total power consumption is 31.44 W. The temperature reaches its minimum value of 4.81°C from 29.12°C in 280 seconds (about 4.6 minutes) using the traditional liquid-cooling system. The drawn current values of the traditional liquid-cooling system are 2.59A, 0.07A, and 0.27A for the TEC, the fan, and the water pump, respectively, the total power consumption value is 35.16 W.

The test result values of these system setups are processed. Table 1 shows the measured and processed data of the three systems when the three cooling systems run for 120 seconds. The maximum temperature difference is achieved using the novel cooling system. The results show that the novel system is the most efficient system to dissipate the TEC hot side heat, saving power 9.74 W and 7.26 W compared to the traditional air-cooling system and the traditional liquid-cooling system, respectively.

Parameter	Air-Cooling	Trad. Liquid-Cooling	New Water-Cooling
ΔT (°C)	17.68	22.68	28.13
Time (Sec)	120	120	120
Current (A)	2.62	2.93	2.88
Power (W)	31.44	35.16	34.56
CoP (°C/W)	0.5625	0.6442	0.8136

Table I: System performance of different cooling systems

The novel water-cooling system eliminates the challenges in the literature survey (Section II) in [3-11], which are described as follows. The researchers in [3] focused on the cost prospective in the expense of the cooling rate of the AC, the researchers in [4] used thermosyphon to improve heat dissipation, which depends material properties. The authors in [5] used pulse operation technique that has limitations of short-lived and effectiveness [7]. The researchers in [2, 6, 8-9, 11] focused on the material aspects to improve thermal resistance and ZT, which require a lot of investigations and analysis. The work in [7] was based on multistage TE modules that improved the heat performance but in the expense of the cost from using multistage modules. The researchers in [10] focused in heatsink design that required a fan and increased power consumptions. The proposed novel water-cooling system avoided these challenges of the AC devices in the literature search through integrating water block system to dissipate the heat efficiently. The material and the build of the proposed system are very cheap, without using any specific materials of TECs and multistage modules, where the proposed cooling system enhances the efficiency of the ACs, as listed in Table I. The proposed cooling system improved the CoP and the heat performance in comparison of the convention system by 44.7%, which depends on a simple electromechanical system.

VI. Conclusion and Future Works

This work addressed the growing environmental concerns associated with traditional AC technologies. This study presented a novel heat dissipation system designed to enhance the efficiency of TEC AC systems. The novel colling system included the water block that established a direct connection between the hot side of the TEC and the coolant. Traditional and novel cooling systems are designed and developed, where test profiles are performed to analyze the system performance with respect the energy saving. Experimental results reveal that the proposed water-cooling system outperforms conventional air-cooling and liquid-cooling systems, achieving a CoP increase of 44.7% and 26.3%, respectively. The novel cooling system enhanced installation flexibility, thereby broadening the application scope of TECs in various settings. These advancements contribute to the goal of developing more sustainable and efficient cooling solutions, aligning with global efforts to reduce electricity demand and greenhouse gas emissions.

Future work will focus on optimizing material to improve the ZT values which enhances the CoP to exceed the traditional AC. Overall, this research paves the way for a new generation of energy-efficient AC technologies that prioritize environmental sustainability without compromising cooling. This includes performing finite element analysis using suitable simulation tools to analyze the effect of different material.

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