Smart Travel Mug for Hot and Cold Beverages

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SMART TRAVEL MUG FOR HOT AND COLD BEVERAGES

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ABSTRACT

Disposable cups tend to be a viable solution as a packaging method for hot or cold beverages, but they have adverse environmental impact. They represent a concern for consumers due to the excessive use of trees during production of paper cups and non-biodegradability of plastic cups. The mobility and convenience of reheating the beverage in a microwave oven, for example, encourages the use of disposable cups. In this project, an environmentally-friendly solution is presented to reduce the use of plastic and paper cups that harm the environment. Compared to other existing products, this device maintains a desired temperature of a hot or cold beverage for extended periods of time using insulation and power from a thermoelectric cooler. The proposed design consists of a double-wall mug with outer steel and inner copper cylinders. The base of the copper cylinder is integrated with a thermoelectric cooler and a control system. The development of the device is governed by the performance of preserving desired temperature of beverages for longer times compared to conventional mugs and containers. Testing methods consist of thermal FEA simulation, CFD simulation and physical prototype testing showing a temperature difference of 30 ºC with the added thermal system to the mug.

INTRODUCTION

The advent of travel mugs can be traced back to the 1980s to help people who were travelling preserve the desired temperatures of their beverages. Whether one wants their drink to remain cold or hot, a travel mug helps accomplish the task due to thermal insulation properties. However, the mug is not sealed at all times as the drinking opening at the top remains open leading to heat transfer with the surrounding. The temperature of the contained beverage is greatly affected by the temperature of its surroundings and therefore, hot beverages will lose their optimum desirable temperature and that applies for cold drinks as well.

Styrene and plastic cups are increasingly being utilized for the purpose of carrying these drinks as they can easily be warmed in a microwave without destroying the container. Consumers, therefore, tend to focus on the advantages of disposable cups and not assume the health hazards that can be caused by styrene cups and the environmental liability in utilizing plastic cups. In addition, the reusable mugs are not able to adequately control the temperature of the drink contained in them over extended periods.

The heating and cooling processes can be accomplished by utilizing a variety of methods such as resistive heating and refrigeration cycles respectively. In addition, a micro thermoelectric plate, a Peltier element, functions as a heating and cooling source and operates in small areas. Such elements can also be integrated with a microcontroller and a temperature sensor as a control system. Existing products utilize AC power or 12 V DC power supply from cars' cigarette lighters as a means to provide a steady stream of high current so that beverages are heated rapidly. For the scope of this project, the portability aspect of the design required the use of rechargeable batteries to supply the needed power.

There are numerous challenges facing this design such as cost, portability and effectiveness; the design was estimated to cost approximately $65 compared to a popular product that costs $150 to buy and showed effectiveness for three hours of operation as a portable device. In addition, the device can be manufactured using thermal joining processes such as Tungsten Inert Gas (TIG) welding or heat treating the steel mug to elevated temperatures and quenching it on the copper mug to form a permeant bond. This could pave the way for mass production that leads to reduced costs as governed by the principles of economies of scale

A CAD model of the proposed device is shown in Figure 1. The prototype of the system was built with a double-wall outer steel and inner copper cylinder with a Thermoelectric Cooler (TEC) and a heat sink and fan assembly attached to the bottom. The mug was sealed with a cap of polystyrene foam. A cut-away view of the prototype is shown in Figure 2.

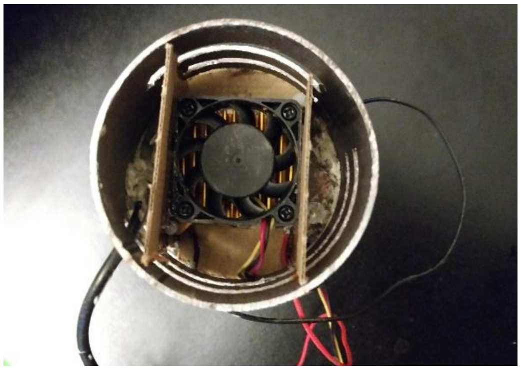
Figure 1: CAD design of the proposed system with the internal parts of the system

Figure 2: Physical prototype of the system with the TEC and the heat sink assembly located inside the steel mug and attached to the bottom of the inside copper mug.

MATERIALS AND METHODS

Design

The prototype relies on the principles of thermoelectric effects in order to both provide and withdraw heat during the heating and cooling of the system respectively. The TEC operates under Peltier effect, in which electrical energy is converted to thermal energy. The advantage of using the TEC over other methods lies in the small size allowing integration in applications where size is constrained. Also, the TEC does not contain moving parts eliminating potential failure during operation despite its low thermal efficiency. The outer cylinder was designed to allow airflow to aid in the heat dissipation of the TEC in case of the cold beverage as the bottom plate of the TEC becomes hot. Slits were machine cut into the outer shell of the mug to allow a forced airflow to cool the fins of the heatsink. To further improve the airflow, thin cardboard sheets were placed in-line with the two last fins of the heat sink leading the air to flow only through the heat sink. This assembly is shown in Figure 3.



Excessive heat in one side of the TEC affects the desired cooling functionality. Based on the thermal circuit of the system and the design constraints, forced convection was deployed to remove the excessive heat as natural convection would require long fins, which cannot be accommodated in such a limited space. To achieve and control forced convection, a box fan was introduced and clamped on the heat sink. With that, simulation results show a temperature difference of 92 K as illustrated in Figure 4. A DC fan type 412 was deployed in the simulation. Also, standard conditions were assumed for the purposes of this simulation, i.e. atmospheric pressure and room temperature. The velocity of air at the fan inlet was determined to be 3.14 m/s based on half of the capability of the fan to account for imperfections. It was determined based on convection coefficient and flow analysis. The heat sink material was selected based on thermal capabilities and cost effectiveness as 1060 Aluminum Alloy. In general, the simulation model was created to represent the prototype regarding parameters such as materials and dimensions.

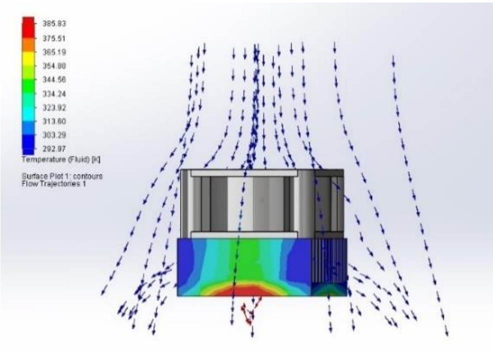


Figure 4: Simulated airflow through the heatsink-fan assembly with 92 K temperature difference.

The prototype was designed to follow the standard 20 oz (591.471 mL) size due to the popularity within the US consumer market. Since the mug is in double wall configuration, with the control system in the bottom, the usable capacity of the mug is reduced to 14 oz (414.029 mL). Bigger sizes would require more power as temperature gradient increases along the copper cylinder; in this case, temperature difference was determined to be 5 ^{o}C as shown in Figure 5. Furthermore, 100,148 nodes and 52,547 elements were used in the simulation mesh. Also, the materials for the following simulation were selected as pure copper for the mug along with silicon for the TEC.

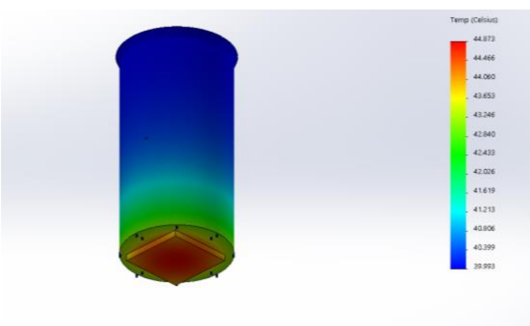


Figure 5: Temperature difference of approximately 5 ^{0}C in the used copper.

Assembly and Development

To build a prototype of the mug, a large diameter copper pipe was cut to the desired length and a copper disc was soldered to the bottom of the pipe using silver solder. Similarly, a large diameter steel pipe was machined with six cuts to allow for heat dissipation as seen in Figure 2 and Figure 3. This steel pipe was not intended to be closed from the bottom to provide easy access for the control system in this development stage.

In general, heating applications consume more current than other applications within the consumer electronics industry. This challenge was addressed with insulation; expanding foam was used to insulate the copper cylinder from the surrounding and reduce heat transfer. The hole in the copper cylinder allowing the temperature probe to penetrate was insulated all around with silicone sealant in addition to the foam to prevent leakage. Even though the sealant used was not FDA approved, in future development phases, a food-grade silicone sealant will be utilized.

The TEC plate in contact with the copper bottom was adhered to the copper cylinder using a thin layer of silver based thermal paste along with a limited amount of epoxy to make the bond permanent. Similarly, the heat sink was installed on the opposite plate of the TEC with the fan clamped with screws to the heat sink. The mug was insulated with a cap of polystyrene foam pressed with a mass of 5 lb (22.241 N) to seal it entirely as seen in Figure 2.

The prototype was driven with a bench power supply for this testing stage and examined for the use of Lithium Ion batteries for future development stages. It was controlled with three relay switches, where one relay, Relay 1 in Figure 6, controlled the entire circuit to activate only when needed. The other two relays acted as a voltage polarity reversal circuit, achieving the desired control of the TEC plate in contact with the copper cylinder's bottom. Figure 6 shows the control part of the system including the power supply, relays and the TEC. Depending on the desired state of the TEC, heating or cooling, Relay 2 and Relay 3 in the Figure will activate and reverse polarity inverting the temperature of the TEC plate in contact with the copper cylinder.

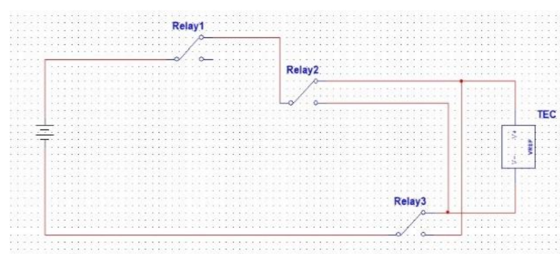


Figure 6: Voltage polarity control circuit showing the power supply connected to the TEC through a control relay and through two relays to control the functioning state of the system.

To monitor the temperature of the beverage and ambient temperature, two temperature sensors were introduced. A water-proof temperature probe was installed inside the copper cup to monitor the temperature of the beverage giving a precise temperature reading of the liquid. The other temperature sensor, a thermistor, measured ambient temperature. Both of those readings were then recorded in an experiment to compare the controlled and uncontrolled drop to room temperature in case of hot beverages and increase in case of cold liquids.

The system was connected for three hours to simulate a battery of 3.7 Ah at 7.4 V as the TEC consumes 1.1- 1.3 A, which would make the battery last for approximately three hours. This particular battery combination, two in series, was chosen due to the high capacity of 18650 batteries as well as their popularity reducing the Cost of Goods and Services (COGS), from a manufacturing perspective. With that, the results can be generalized to higher capacities with the known TEC current consumption.

RESULTS

To test the functionality of the system and evaluate whether it maintains the desired temperature of hot and cold beverages better than conventional mugs and thermoses, water was used to observe natural temperature decay and growth without the proposed system. The data from this test were compared against the results obtained by executing the same experiment with the prototype device. Four tests were carried out for every configuration, i.e. four tests without the system and four tests with the system equipped. During those tests, the cap was removed 10 times for 30 seconds to simulate drinking at random intervals. Figure 7 and Figure 8 show the results of the tests sampling once every 30 seconds.

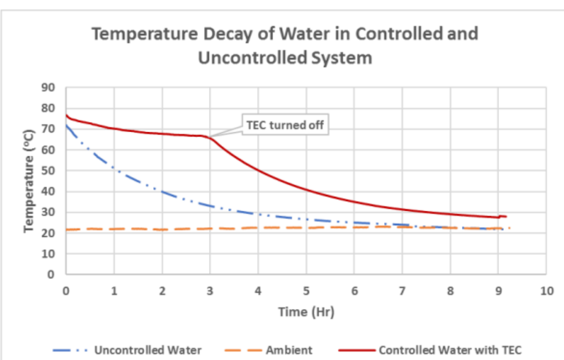


Figure 7: Results of natural and controlled temperature decay of hot water.

Controlled decay refers to the results of water temperature with the system in operation. The results from this test show a better performance of maintaining the temperature of hot water; the steep decay after three hours is associated with turning the system off simulating a 3.7 Ah battery pack.

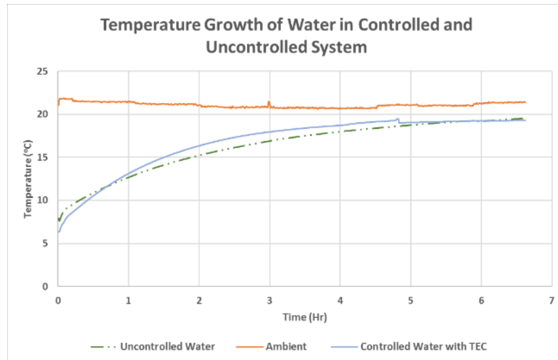


Figure 8: Results of natural and controlled temperature growth of cold water.

Both starting temperature were chosen to represent the consumer behavior, hot beverage will be poured into the mug after boiling or brewing (70-80 ºC) and cold liquid will be poured from the refrigerator (7-8 ºC).

Results from cold testing show improved capabilities within the first hour of operation.

CONCLUSIONS AND FUTURE DIRECTIONS

Development results show a promising functionality of the system to introduce smart mugs that can maintain optimum temperatures of the beverages for extended periods of time for hot beverages as shown in Figure 7, with 30 ºC difference between the proposed design and conventional travel mugs. With improved insulation, the system would maintain the temperature of beverages for longer periods of time as it cannot be confirmed that the copper and steel are insulated evenly throughout the contact surface. Also, the utilized polystyrene foam with the mass does not insulate the container properly compared to the intended approach of threaded ABS cap. Similarly, an even thin layer of thermal paste cannot be confirmed as it was applied by hand. As a result of that, the desired heat transfer rate is affected causing faster temperature change. In addition, the heat penetrated through to the plate in contact with the copper due to impurities of the TEC used in this project even with sufficient cooling with the heat sink and fan producing unanticipated results in the case of cold water.

Further research and investigation are required to determine the optimum thermal interfaces to maximize heat transfer between the TEC, the copper mug and the heat sink. Also, the 7.4 V, 3.7 Ah Lithium Ion batteries can power the system for more than 3 hours as shown in Figure 7 and will aid in the portability aspect of the proposed design. Pulse Width Modulation (PWM) integration can further improve power consumption of the prototype and optimize TEC performance leading to the conservation of desired temperatures of hot and cold beverages for longer periods. Furthermore, anti-oxidation coatings for copper will be applied for further development stages to prepare the system to a product stage.

Modern manufacturing techniques and automation will assure the accuracy of an even distribution of insulation and thermal interface leading to an improved performance.

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