2.671 Measurement and Instrumentation
Tuesday 2-5
Prof. Nicholas Makris
December 14, 2017

EFFECTS OF MATERIAL CHOICE AND WIND SPEED ON EVAPORATIVE COOLING

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ABSTRACT

In regions without electricity, farmers and consumers need a way to keep food chilled to reduce food spoilage. One potential solution is the pot-in-pot refrigerator which cools food by evaporating water. The device stores water in a medium, usually sand, sandwiched between an inner pot which contains the food and the outer pot from where the water can evaporate into the air. Two factors that affect the pot-in-pot refrigerator's cooling performance are the water-storing material and the wind blowing over the device. These two effects were quantified with a factor called the cooling coefficient by placing wet cotton fabric, polyester-cotton fabric, and garnet sand on a hot aluminum block and measuring the temperature of the block and ambient air at controlled wind speeds of 0, 1.8, and 3.2 m/s. Both material choice and higher wind speed can improve the cooling performance with statistical significance. Sand with 3.2 m/s wind cooled the block most rapidly with a cooling coefficient of $(7.78 \pm 0.71) * 10^{-4} \frac{1}{s}$.

INTRODUCTION

Refrigeration is fundamental to today's global economy, especially in its most well known application of chilling food to prolong its shelf life. The extended shelf life increases the time and distance that food can travel, thereby allowing farming on agriculturally productive lands and delivery of food to where people live. However, modern refrigeration requires electricity for which billions of people still lack steady access (1). In unelectrified areas which are often home to low-income populations such as in rural regions of India (1), there is a vital need to chill food with minimal cost in order to reduce food spoilage and therefore reduce hunger (2).

Evaporative coolers, of which the pot-in-pot refrigerator is one type, draw heat away from food by evaporating water. Thus, it does not require electricity. The overall performance of an evaporative cooler can be described with a parameter called the cooling coefficient. The cooling coefficient can change with the choice of the water-storing medium and with the wind speed over the surface of the pot. Using a simplified model with an aluminum block as the object to be cooled, the cooling coefficient was calculated by individually measuring temperature over time for three wet materials at three wind speeds as they rested on top of the aluminum block. These materials were cotton cloth, synthetic fabric, and garnet sand. The wind speeds were 0 m/s, 1.8 m/s, and 3.2 m/s. The cooling coefficients for each wind and material combination was compared to determine how each of the two factors affect cooling performance.

BACKGROUND AND THEORY

POT-IN-POT REFRIGERATOR

The pot-in-pot refrigerator is a technology that was developed thousands of years before the advent of electricity to address the problem of food storage (3). However, with billions of people across a number of countries lacking access to reliable electricity as seen in Fig. 1, there is still a need for electricity-free methods of cooling.

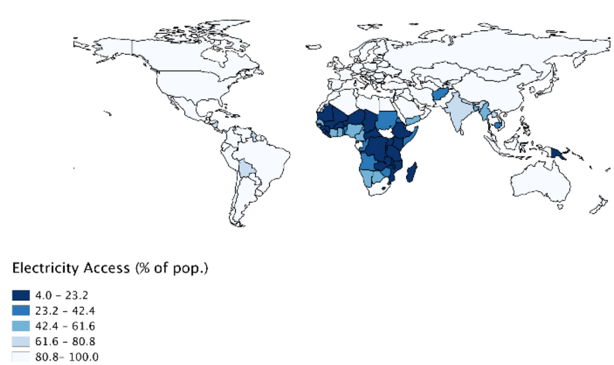


Figure 1: Electrification around the world. Darker colors denote lower levels of electrification (4).

While Fig. 1 is insightful, another factor to consider which is not shown is the disparity between electrification in urban and rural areas within nations. A majority of a nation's population may reside in electrified urban centers which would increase a nation's electrification rate, but it would mask the unelectrified rural population. Thus, the need for refrigeration without electricity may be more widespread than Fig. 1 indicates.

Fig. 2 looks at undernourishment levels which can be viewed as the need for a stronger system to support the supply of food. Technologies like refrigeration could help. However, there is an overlap between lack of electrification and undernourishment, meaning that modern refrigeration would not readily work. While correlation versus causation between electrification and undernourishment is not examined here, a potential link may be the inability to refrigerate food leading to premature food spoilage so then less food is available to eat.

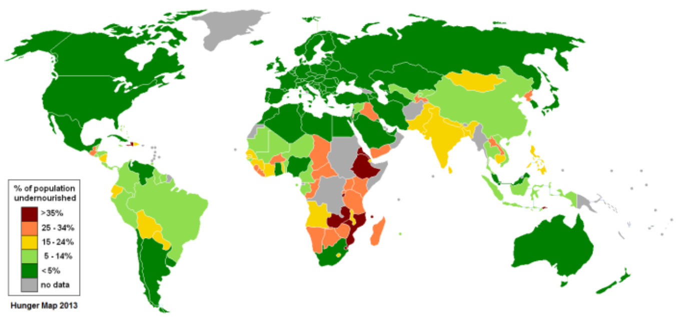


Figure 2: World map of undernourishment (5). Note the overlap of undernourishment with the lack of electrification in Fig. 1.

Primarily in the areas which face undernourishment and electrification, there is a role for evaporative cooling to provide some amount of cooling capacity with no electricity requirement. The pot-in-pot refrigerator utilizes the evaporation of water, which is thermodynamically and economically free within a range of environmental conditions, to transfer heat from the stored food to the ambient air. The process works similarly to how a human sweats: water on the surface of their skin evaporates into the air, drawing heat away from the body. As seen in Fig. 3, the differences from sweating are that the water in the pot-in-pot refrigerator comes from a saturated medium between the two pots, and food is being cooled instead of a person's body.

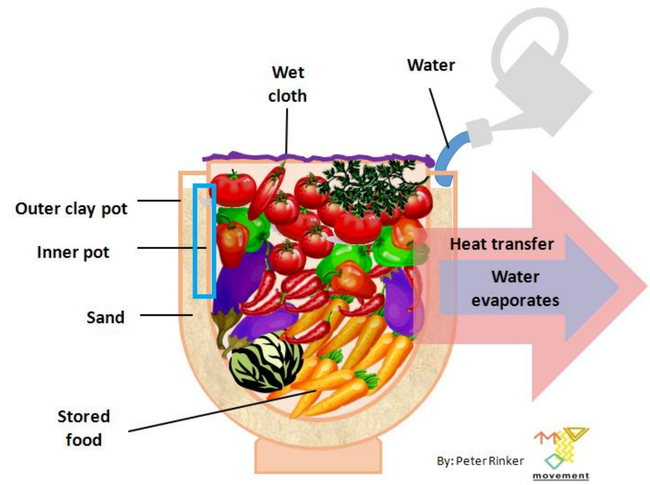


Figure 3: Cartoon cross section of a pot-in-pot refrigerator (6). Water is poured into the sand between the two pots and evaporates through the outer pot, cooling the food in the inner pot. The blue box marks the portion of the device analogous to the experimental setup.

The pot-in-pot refrigerator pictured above shows the food stored in the inner pot resting on a layer of sand in the outer pot. Water is added to the sand and evaporates through the outer pot, transferring heat away from the food. The water must be replenished periodically to restore the water lost to evaporation. The analog to perspiration would be rehydrating. Continuing the analogy, for the same reasons that the effectiveness of sweating depends on humidity and other ambient conditions, the pot-in-pot cooler has a range of operating conditions that affect its cooling capability. Fig. 4 shows a map published in a study that considers humidity among other factors to determine areas that could feasibly build and use pot-in-pot refrigerators (7).

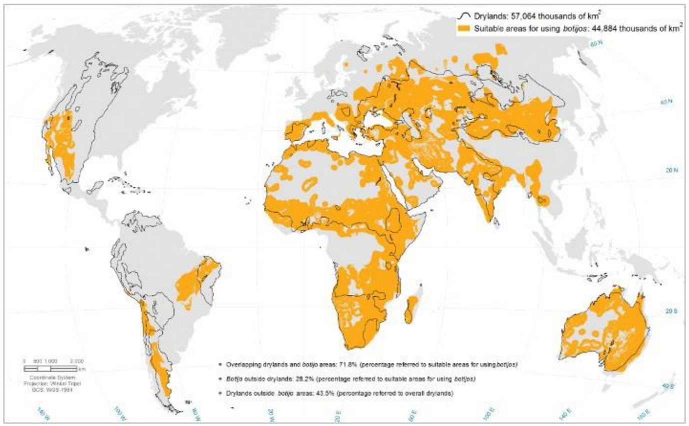


Figure 4: Shaded areas mark the potential use of pot-in-pot coolers around the world according to a study that factored in ambient temperature, humidity, drinking water supply, and availability of ceramics (7).

Unfortunately, pot-in-pot coolers cannot be utilized everywhere, but importantly, they work in many areas highlighted in Fig. 1 and 2 that show a need for electricity-free refrigeration. One academic review which focused on the use of evaporative coolers (a broader field than pot-in-pot coolers) in India, cited studies that achieved 10 – 16 ˚C cooling with ambient air conditions ranging from 39 – 44 ˚C (2). Pot-in-pot refrigerators can provide useful refrigeration, extending the shelf life of some foods by a factor of ten, from two days to twenty (2). It would be useful to millions if not billions of people to improve the function of pot-in-pot refrigerators.

Taking a step aside from discussing the utility of pot-in-pot refrigerators to comment about terminology, this paper will use "refrigerator" in regards to the "pot-in-pot refrigerator" interchangeably with "cooler" and "chiller". Although the word "refrigerator" is normally used to describe the electric household appliance, this paper uses "pot-in-pot refrigerator" since it is the common phrase used to describe the device.

MATERIALS USED IN EVAPORATIVE COOLING

As shown in Fig. 3, the filler material between the two pots is silica sand, which can be found in river beds. The pots themselves are made of clay. The outer pot is permeable to water while the inner pot is not. This allows water to evaporate into the surrounding air but not soak the food. The combination of sand and clay are often chosen because they are relatively inexpensive and locally available to the people building and using pot-in-pot coolers (2). Since silica sand was not locally available for the experiment, garnet sand was used. Garnet sand was deemed to be a suitable alternative for the experiment since similar material properties allow it to serve as a substitute for silica sand as the abrasive material in water jet cutters which were locally available for the experiment.

Other designs of evaporative coolers call for different materials. For example, one design uses a metal or wooden crate covered with a thin wet material. In this design, the water soaked material is directly exposed to the air, instead of being sandwiched between two pots in the pot-in-pot cooler. The large surface area of the covered crate design increases the evaporative cooling effect. In these other designs, fibrous materials such as coconut, cane, hemp, and jute are used to hold water (2). This is mentioned because cotton and poly-cotton which are both fibrous materials were used in the experiment. While the experimental design (discussed in Section 3) was based on the pot-in-pot design, it may similarly model covered-crate and other designs which were not directly considered when designing the experiment.

Additionally, while cotton and poly-cotton do not seem to have similar material properties as sand, these two materials were chosen because they have similar costs and availability as sand. Cotton and poly-cotton can be easily sourced from shirts and other clothes and as a result are relatively inexpensive (8). This was the case for this experiment as the cotton and poly-cotton materials were cut from t-shirts.

While fundamental material properties were not studied in this experiment, they can be used to develop a predictive model of evaporative cooling capabilities. Some important material properties are: porosity, permeability, density, specific heat capacity, and heat conduction (9, 10). Studies, notably in the fields of architecture and civil engineering when looking at thermal comfort (3, 11), have used these parameters to numerically simulate evaporative coolers and then validated their models empirically (8, 9, and 12). For the experiment described in this paper, these material properties were not directly measured but their total effect was studied. The overall performance was evaluated by the cooling coefficient determined from a lumped parameter model of temperature over time. The lumped parameter method combines all factors such as the cooling material and wind effects into one value.

EVAPORATION

The key component of evaporative coolers lies in its name – evaporation. As water changes state from liquid to gas, it absorbs heat from its surroundings, some of it from the air, some from the pot-in-pot cooler. As water absorbs this heat, the pot-in-pot refrigerator becomes colder.

The theoretical evaporative cooling potential is determined by the difference between the dry bulb and wet bulb temperature (2). A mercury thermometer can be used to measure the dry bulb temperature. Wet bulb temperature is measured as the lowest temperature achieved by letting water evaporate into the air until the air is saturated, meaning 100% humidity. In practice however, pot-in-pot coolers do not achieve this theoretical potential since factors such as materials and wind speed affect its cooling performance.

As mentioned in Section 2.1 with the analogy to sweating, the more saturated the air is, the less cooling that can be achieved by the pot-in-pot cooler. Unfortunately, the pot-in-pot cooler directly evaporates into the surrounding air, stifling further evaporation. The natural solution which prevents this buildup of humidity is wind. It brings in dryer air while blowing the humid air away from the outer pot's evaporative surface, aiding the cooling effect. If left inside, the evaporation from the pot causes the humidity to increase, negatively affecting the pot-in-pot cooler's performance. While individual use of the coolers may vary, pot-in-pot coolers are typically placed outside on the ground under shade to maximize the evaporative cooling effect.

NEWTON'S LAW OF COOLING

In this experiment, the cooling performance was characterized for several water-soaked media – cotton cloth, synthetic fabric, and garnet sand – as well as the control condition of no material at three wind speeds – 0, 1.8, and 3.2 m/s. The overall effects of material choice and wind speed on cooling performance can be quantified by a lumped parameter called the cooling coefficient. By measuring the block's and ambient air's temperatures over time, the data can be fit to an exponential decay model known as Newton's Law of Cooling, shown in Equation 1. From that, the cooling coefficient denoted as C with units of $\frac{1}{second}$ can be determined. $T(t)$ is the block temperature over time, T_a is the ambient temperature, and T_0 is the initial temperature of the block, all measured in degrees Celsius.

$$T(t) = T_a + (T_0 - T_a)e^{-Ct} \qquad (1)$$

PRIOR RESEARCH ON EVAPORATIVE COOLING

A study of porous building materials investigated the effect of water content on evaporation rate (11). In the constant drying rate period, the material is thoroughly saturated, so water can readily evaporate into the air. In the falling drying rate period, water has to diffuse through the material before reaching the evaporative surface. While the experimental trials for this paper began in the constant drying rate period, it is unknown if the trials fell into the falling drying rate period. An interesting result from that study was that materials can yield a higher evaporation rate than the surface of free water. This seems surprising, but the paper suggests that one reason could be that the material's surface irregularities create a larger effective surface area than still water (11). An additional note from this study is that evaporation increases the concentration of minerals left behind in the material. The concern for pot-in-pot coolers is that additional minerals may decrease how well water can diffuse through the outer pot before evaporating.

Using numerical simulation, another study looked at how evaporation from soil was affected by wind flow at different speeds. They found that at low velocities, increasing the wind speed increases the evaporation rate (10). At higher velocities, increasing wind speed had less effect. The explanation for this was that at high wind speeds, the evaporation was limited by how fast water could diffuse through the soil and not limited by the rate of evaporation from soil to air. This study shows that evaporation rates and thus the cooling coefficient vary non-linearly with wind speed.

These two studies highlight the effects that materials and wind speeds can have on evaporative cooling as well as suggest interesting avenues to explore which are discussed in the conclusion.

EXPERIMENTAL DESIGN

From Fig. 3, the section in the blue box turned 90° clockwise as pictured in Fig. 5 is the portion of the pot-in-pot refrigerator from which the experimental model was developed, pictured in Fig. 6. The analog of the sand layer from the pot-in-pot cooler to the experimental setup is the rectangle labeled "wet material" in Fig. 6. The wet materials tested were cotton fabric, polyester-cotton fabric, and garnet sand. The control condition was no material on the block, exposing a bare aluminum surface. These materials were each tested at wind speeds of 0, 1.8, and 3.2 m/s.

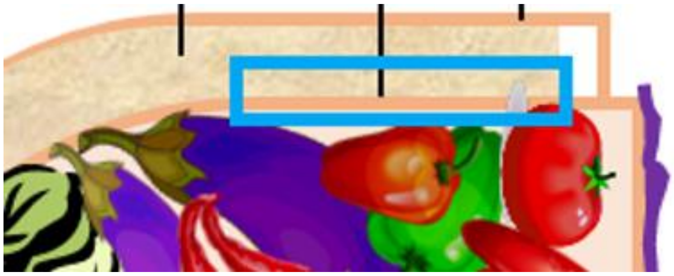


Figure 5: Experiment models the area in the blue box, a section of the pot-in-pot refrigerator from Fig. 3 turned 90˚ clockwise.

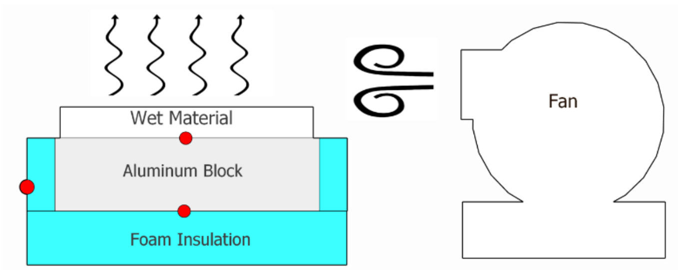


Figure 6: Schematic of experimental setup with a fan blowing over the water-soaked material. Temperature sensors (red dots) are placed to record the temperature at the top and bottom of the block and the ambient air. These are connected to Logger Pro data collection units (not pictured).

The aluminum block in Fig. 6 had dimensions of 16 cm x 16 cm x 2 cm. The block was encased with foam of thickness 2 cm to isolate the heat transfer through the upper surface to better approximate a pot-in-pot refrigerator. Vernier surface temperature sensors which have a range of -25 to 125 ˚C with an accuracy of ± 0.2 ˚C, were taped to the center of the top and bottom surfaces of the aluminum block. The temperature of the bottom surface is analogous to the temperature that the food in a pot-in-pot cooler is stored at. There was a third temperature sensor placed on the exterior of the foam insulation which faces away from the fan. The mean temperature from this sensor was used as the ambient temperature. A centrifugal fan was placed 15 cm in front of the leading edge of the aluminum block, and a variable transformer controlled the fan's power between 0-100%. An Extech anemometer was used to convert the wind flow from a percentage to speed. The anemometer has a range of 0.8 to 12.0 m/s with an accuracy of 2%. The variable transformer settings of 0%, 40%, and 80%, correspond to wind speeds of 0 m/s, 1.8 m/s, and 3.2 m/s.

This simplified setup focuses on the how wind blowing over a wet material placed on the block affects the cooling rate of the block underneath, which represents the inner clay pot. One decision made in this simplified model was to exclude the analog of the outer pot layer. Since it was unknown how visible the results of the experiment would be, the exclusion of the outer pot layer was made to make the effects of material choice and wind speed more pronounced.

MEASURING THE COOLING COEFFICIENT

Each material option (cotton, poly-cotton, sand, and control) was tested three times at each wind speed (0, 1.8, and 3.2 m/s) in the experimenter's dorm room which has relatively consistent ambient temperature and humidity. Since the experiment took place indoors, the effects from sunlight were negligible. In realistic conditions where pot-in-pot coolers are placed in the shade, the direct effects of sunlight on the devices can be neglected as well.

To mimic the heat that food freshly picked from farms would release in a pot-in-pot cooler, a heat lamp warmed up the block to 40 ˚C as measured at the block's bottom surface. Then, the heat lamp was turned off. Quickly but carefully, the water-soaked material was placed evenly over the exposed surface of the block, the fan turned on (if needed), and the data collection started through Logger Pro 3.14.1 with a sampling rate of 1 Hz for 1000 seconds (about 16.6 minutes). The measurements recorded to Logger Pro were the three surface temperatures (˚C) and relative humidity (%).

An Ohaus balance was used to measure a consistent mass of water to add to the wet materials for each trial. The balance has a 2000g capacity and a resolution of 0.1g. A Vernier relative humidity sensor was placed some distance away to record ambient humidity and confirm that each trial took place within a small range of humidity levels. The relative humidity sensor has a range of 0-95% with a resolution of 0.04% RH.

The data from Logger Pro was exported and analyzed in MATLAB R2017b using standard model-fitting functions. From this, the cooling coefficient was determined. Calculations to determine statistical significance between cooling coefficients were performed in Microsoft Excel 2016.

RESULTS AND DISCUSSIONS

The ambient temperature and the temperature of the bottom of the aluminum block was measured over time for each material and wind speed combination. These materials were wet cotton, polyester-cotton, and garnet sand, as well as a control condition of a bare surface. These materials were tested at wind speeds of 0, 1.8, and 3.2 m/s. Newton's Law of Cooling was fit to the temperature vs. time data to determine the cooling coefficient. By this parameter, the effects of material choice and wind speed were compared to the control condition and to the other material choices at each of the three wind speeds. The analysis shows that placing a wet material of the block improves the cooling performance compared to the bare surface. Additionally, sand generally performs better than the other materials at wind speeds of 1.8 and 3.2 m/s, but in the 0 m/s case, large uncertainties in the cooling coefficient value for sand prevents a comparison.

COMPARISON OF COOLING PROFILES

When looking at a set of individual trials conducted at 3.2 m/s wind pictured in Fig. 7 for a relative comparison of the time-temperature profiles for the different materials, sand shows the largest temperature drop over the data collection period. These comparisons of raw data between trials were done to establish an initial ranking of the materials to build an intuition before conducting analysis. Additionally, the temperatures shown in this figure correspond to the bottom surface of the block which is the location that represents the internal temperature of a pot-in-pot refrigerator.

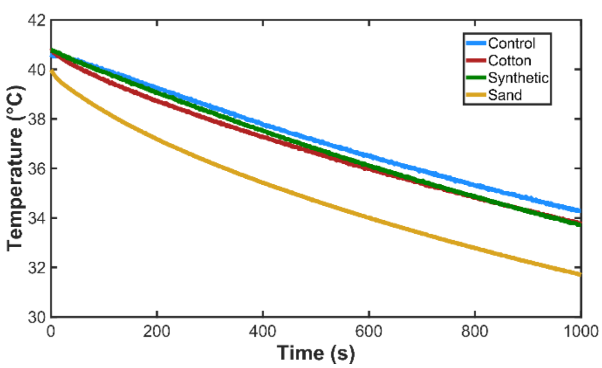


Figure 7: Temperature at the bottom surface of the block as a function of time with wind speed of 3.2 m/s. Note the initial temperatures are different, so direct comparisons are difficult to make from this graph.

However, during experimental testing, it was difficult to have each trial start with the exact same temperature of 40.0 ˚C. Thus in Fig. 8, each trial is normalized by its initial temperature to provide a second pass visual comparison.

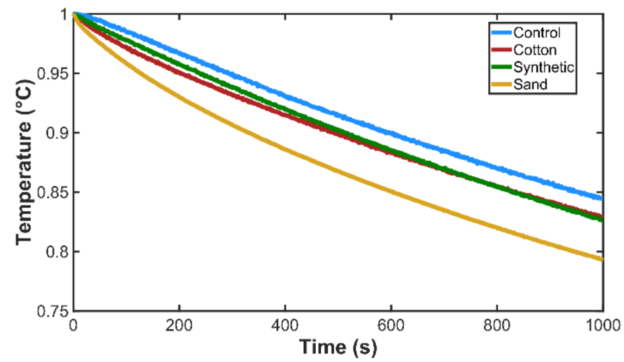
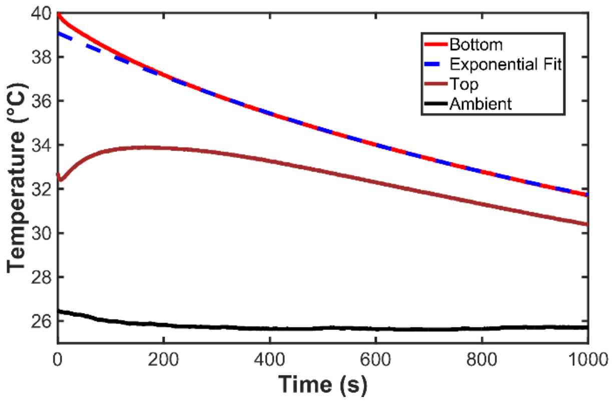


Figure 8: Ratio of temperature at time *t* to initial temperature over the data collection period. Note the improved cooling by placing a wet material on the block.

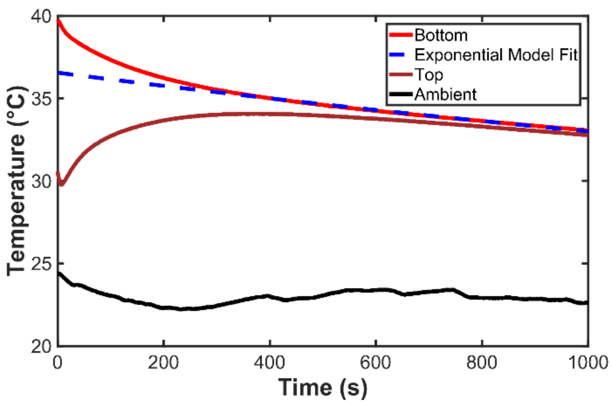
For the set of trials used in Fig. 8, the data shows that adding a wet material improves the cooling performance by some visible amount. In the case of sand, this effect was most noticeable, increasing the total cooling by about 5% compared to the control condition. In the larger context of using evaporative coolers for food storage, a thousand second cooling period under realistic wind conditions (3.2 m/s) brought about a useful 16-20% total drop in temperature which is about 8 ˚C. While more time would lower the temperature further, the evaporative cooling effect exponentially decays with time, so a longer testing period would not have yielded additional useful data.

FIT OF EXPONENTIAL MODEL

After the preliminary comparative evaluation of the data, Newton's Law of Cooling shown in Eqn. (1) was fitted to the data. From this fit, the cooling coefficient was measured. While Newton's Law of Cooling is a good, simple approximation of the evaporative cooling processes happening in the experiment, it is not exact. Figure 9 shows the fit of Newton's Cooling model to two trials – one where the fit is close, another where the fit is more noticeably diverging from the data.



(a)



(b)

Figure 9: (a) Sand with wind speed of 3.2 m/s. (b) Sand with wind speed of 0 m/s. Notice the difference in the fit curve towards the beginning of the data collection period.

An important consideration is that the model is fit to the data between 300 - 1000 seconds. In this range, the model fits the data well in both (a) and (b). The reason for the delayed start is to exclude the thermal shock that occurs to the aluminum block when the wet material is placed onto it. Regardless, the goodness of fit, or lack thereof, is reflected in the uncertainty of the cooling coefficient value. While it was beyond the scope of this experiment, improvements can be made to the model to better account for the effects of evaporation. By comparing the results of studies such as Davarzani et al. and Goncalves et al. described in Section 2.5, a better model could be developed to incorporate the effects of wind and material choice. In effect, this would "un-lump" the lumped parameter model of Newton's Law of Cooling from the one value of the cooling coefficient to several parameters.

MATERIAL AND WIND EFFECTS

Once the cooling coefficients for the trials were calculated, they were compared as presented in Fig. 10. Each data point and error bar plots the mean and uncertainty from the three trials conducted per material and wind speed pair. It shows that sand performs better than the other material conditions at all wind speeds, albeit with large uncertainty in the no-wind case. With a 3.2 m/s wind, sand has the highest cooling coefficient of $(7.78 \pm 0.71) * 10^{-4}\ \frac{1}{s}$ which is about 46% higher than the control condition, an exposed aluminum surface. The synthetic and cotton perform relatively equally at all wind speeds, both with higher cooling coefficients than the control condition.

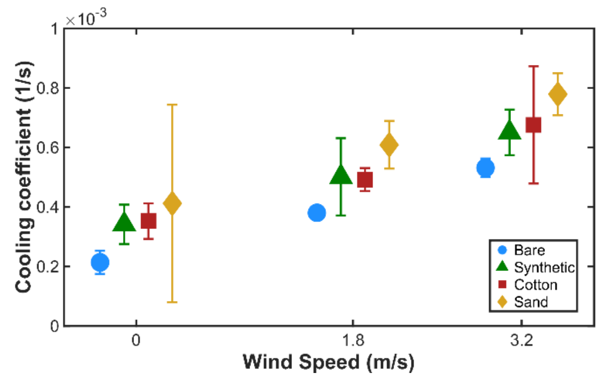


Figure 10: Cooling coefficients plotted as a function of wind speed and the markers organized by material type. The data points are staggered at each wind speed to improve readability.

While Fig. 10 provides a simple representation of the key findings that answer the research objective to investigate the effects of material choice and wind speed, the visual format precludes a quantitative comparison. Table 1 compares the difference in mean values of the cooling coefficients of the wet materials – cotton, poly-cotton, and sand – in comparison to the control as well as to each other.

Table 1: The hypothesized mean differences with units of $\frac{1}{s}$ (left) with corresponding confidence level (right). (a) Comparison of the wet materials to the control case, a bare aluminum surface. (b) Comparison between the material choices. The mean differences are multiplied by a factor of 10^{-3}.

	Wind Speed (m/s)		
	0	*1.8*	*3.2*
Cotton > Bare	0.08	0.07	0.01
Poly-Cotton > Bare	0.06	0.03	0.05
Sand > Bare	0.03	0.14	0.18

**10^(-3)*

	Wind Speed (m/s)		
	0	*1.8*	*3.2*
Cotton > Bare	95%	95%	90%
Poly-Cotton > Bare	95%	90%	95%
Sand > Bare	85%	95%	95%

	Wind Speed (m/s)		
	0	*1.8*	*3.2*
Cotton > Poly-Cotton	-	-	-
Sand > Cotton	-	0.04	0.01
Sand > Poly-Cotton	-	0.01	0.05

**10^(-3)*

	Wind Speed (m/s)		
	0	*1.8*	*3.2*
Cotton > Poly-Cotton	95%	95%	95%
Sand > Cotton	95%	95%	85%
Sand > Poly-Cotton	95%	90%	95%

While a majority of the hypothesized mean differences between the wet material and bare could be found with 95% confidence as seen in Tab. 1 (a), certain pairs of material and wind speed had large uncertainties which requires lowering the confidence interval to establish a hypothesized difference in the cooling coefficients. These three pairs with lower confidence levels are the same ones in Fig. 10 with the three three largest error bars. To reduce this uncertainty and improve the statistical significance, future research should carry out more trials. Tab. 1 (b) shows that cotton and poly-cotton have statistically indistinguishable differences in their cooling coefficients at each wind speed. This means either material could be used interchangeably to produce the same cooling performance. Additionally, while all materials outperformed the control in the no-wind case, the difference of the cooling coefficients between the materials were not statistically significant. Again, conducting more trials to lower the uncertainty may provide more insight in these comparisons.

CONCLUSIONS

A simplified model of a pot-in-pot refrigerator was built to study the effects of material choice and wind speed on cooling performance by calculating the cooling coefficient. At three wind speeds – 0, 1.8, and 3.2 m/s – wet cotton, polyester-cotton, and garnet sand were compared to the control condition of a bare aluminum surface. First, the data shows that placing any wet material on the block improved the cooling rate at all tested wind speeds compared to the bare aluminum surface. Second, higher wind speeds improved the cooling performance for all the wet materials as well as for the control case. Finally, wet sand at the fastest tested wind speed of 3.2 m/s cooled the block most rapidly with a cooling coefficient of $(7.78 \pm 0.71) * 10^{-4}\ \frac{1}{s}$.

The results support the precedent of using sand as the water-soaked medium in pot-in-pot refrigerators. Additionally, the data supports the idea that if sand is not readily available, cotton and poly-cotton which could be easily sourced from fabrics, can serve as substitutes with similar cooling performance as sand. The analysis on the effects of wind speed suggests that between two equally accessible locations, one should place the pot-in-pot refrigerator in the windier location for more cooling.

The simplified experimental model excluded the effect that the pot-in-pot refrigerator's outer pot would have in order to focus on the effects that material choice and wind speed would have on cooling. Since these effects have now been studied, future research should investigate how the outer pot layer would affect the cooling performance. Extending this research in the other direction, another avenue of exploration would be to build a new experimental model and measure the effects that material choice and wind speed have on other designs evaporative coolers in which the wet material is directly exposed to the air. Another extension would be to change the design parameters like material choice that would not significantly increase the cost or complexity of evaporative coolers. The salinity of the water added and the thickness of the material are two such parameters. Stepping back to the original motivation of this work, further research should be pursued because even incremental improvements to pot-in-pot refrigerators and evaporative coolers can help solve a large problem at the intersection of undernourishment and lack of electricity.

ACKNOWLEDGMENTS

Special thanks to Dr. Barbara Hughey, Prof. Nicholas Makris, and Prof. Ming Guo for their help and advice with the project. Additionally, thanks to Thalia Rubio for her feedback on the writing, and Christine Sherratt for helping to find prior research.

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