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Research Article

Cooling Beer with a Wet Paper Towel

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Beer is a drink often stored warm but served cold, a fact that has led to the development of many ways to cool beer and other beverages rapidly. One method suggests that wrapping a beer in a wet paper towel accelerates the cooling in a freezer, but the effectiveness of this method has been debated across the internet. Does a wet paper towel slow cooling by insulating a beer, or does evaporation from the towel enhance cooling? We performed low-cost, easily reproducible experiments and simulations to answer these questions. We employed a Radau, finite-volume method to solve the heat equation in cylindrical coordinates and simulated each material using the best available thermal conductivities, densities, and specific heats. Experiments were performed in the presence of varying levels of advection in the surrounding air. We found increasing advection by placing beers near the freezer fan reduced the cooling time (70°F (21.1°C) to 45°F (7.2°C)) by 60%-70%; the wet paper towel had a negligible impact. With two lower levels of advection, we found that the wet paper towel reduced the cooling time by approximately 25%. Experiments with multiple thermometers were used to generate time-space diagrams that showed the evolving radial temperature profile in materials. Infrared images revealed convection patterns caused by the warm bottle, even when the bottle was protected from airflow from the fan. Our simulations agreed with our data when we used boundary conditions that mimicked convection. This agreement was also evident when comparing data from an environment without air advection, implying the presence of natural convection.

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I. Introduction

Many drinks are enjoyed most in some optimal temperature range; for example, we enjoy coffee at 200°F (93.3°C), white wine at $45-50^{\circ}$F ($7.2-10^{\circ}$C), red wine at $45-65^{\circ}$F ($7.2-18.3^{\circ}$C), warm sake at $100-115^{\circ}$F ($37.8-46.1^{\circ}$C), cold sake at $50-60^{\circ}$F($10-15.6^{\circ}$C), and beer at $35-45^{\circ}$F($1.7-7.2^{\circ}$C). It is generally easier to heat a drink than to cool one, but the challenge of rapid cooling has inspired many quick-cooling methods. Examples include adding frozen items to drinks,[1] submerging drinks in salty ice baths,[1][2][3] and wrapping a wet paper towel around a drink's container and placing it in a freezer.[1][2][3][4][5] Here, we focus on the wet-towel method applied to a bottle of beer. Proponents of this method claim that evaporation from the towel enhances heat removal from the beer.[1][2] Opponents claim that the wet towel acts as insulation that slows the cooling of the beer.[1][4]

These claims have been tested experimentally, often with conflicting results, but the results have generally supported the claim that a wet towel insulates the beer bottle and slows cooling.[4][6] Experiments with water bottles,[6] however, suggest that a wet towel used together with advection driven by a fan shortens cooling times. To explore these claims further, we performed physical and numerical experiments and derived insights from our results.

In our experiments, we were careful to isolate different processes to estimate their importance. For example, in some experiments, we used a closed plastic bin to block air advection caused by the fan in the freezer. We took zero- (bulk) and one-dimensional (radial) measurements of multiple bottles to gather statistics in experiments that employed wet towels and three levels of advection (air blocked from the fan, distant from the fan, and next to the fan).

In addition to addressing the utility of the wet-towel method, more generally we wish to illustrate how everyday questions can be answered scientifically by combining insights gained through both numerical modeling and experiments. Other examples of this approach include studying how to bake a cake, [7] exploring why bubbles sink in Guinness beer, [8] measuring the force required to use a French press, [9] and improving the yield of espresso.[10] We take a pedagogical approach in order to reach a broad audience, and we suggest how to approach other everyday problems with modeling and inexpensive experiments.

The experiments presented here are approachable and reproducible by students at an undergraduate level and up. We intentionally utilized inexpensive equipment in our experiments so that students could easily reproduce our results. In our supplement, we include descriptions of two additional experiments that explore validating thermometer calibrations and the evaporation process. We also list many ideas for future experiments. All of these experiments are aimed at an undergraduate level.

Our model in the main document is based on the ubiquitous Fourier's law.

We greatly extend this modeling approach in the supplement. We begin with a hydrodynamic description of our experiments and apply successive simplifying assumptions to derive multiple models to illustrate model-building strategies. Finally, our supplement also explores our numerical methods in more depth.

The rest of the paper is organized as follows. In Sec. II, we describe the experiments we performed for this study. We begin with bulk measurements of cooling beers before moving on to radial measurements of cooling beers. Lastly, we describe experiments in which we used an infrared camera to visualize natural convection. In Sec. III, we compare our radial measurements with solutions to a one-dimensional heat equation. We discuss our conclusions and provide an outlook in Sec. IV.

II. Experiments

For each of our experimental configurations, we used four beers of a single type (Bright White Ale, Bell's Brewery, Kalamazoo, MI, USA). All of our cooling experiments were conducted in an industrial walk-in freezer and employed four dual-channel thermometers (Proster Trading Limited, Hong Kong) to improve statistics and to allow for multiple, simultaneous experimental configurations.

It is almost certain that advection plays a large role in the cooling process; thus, to control for air advection, we created high-, low-, and no-advection environments. These environments both act as control environments in our experiments and can be mapped onto the amount of space available in a real freezer, with a high-advection environment corresponding to an empty freezer and a no-advection environment corresponding to a fuller freezer. These different tiers of advection allow us to address, for example, whether a method works better in an empty freezer or a fuller freezer. We minimized air advection (but, see Section IIC) by placing bottles inside a bin with a lid in the freezer, and we created a low-advection environment by placing beers next to the bin on the floor of the freezer (see Figs. 1(b) and 1(d)). To create a high-advection environment, we placed the beers near and in line with the freezer's fan at the top of the freezer (see Fig. 1(f)).

A. Zero-Dimensional Beer Cooling

We began by taking 0D, bulk measurements of the beers as they cooled in our various experimental conditions. These experiments were "0D" in that we opened each beer and placed a single thermocouple as close to the center of the bottle as possible. Our results are shown in Fig. 1, where the experimental configurations are shown in the photographs in the right column. In panel (a), the bottles were placed in a bin to protect them from airflow. Four of the bottles were wrapped with a paper towel, and four without; their temperature evolution is shown as orange squares and blue points, respectively. Similarly, in panel (c), the temperature evolution of wrapped and unwrapped bottles placed next to the bin is shown. Finally, panel (e) examines bottles placed next to the fan (seen at the upper left of the bottom photograph). In the left column of Fig. 1, we plot the means and standard deviations of temperatures for each of our 0D experimental

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configurations. A gold band is added to the plots that represent "good beer-drinking temperatures" in the range $35 - 45^{\circ}$F$(1.7 - 7.2^{\circ}$C). We continued to make measurements until beer temperatures approached water's freezing temperature.

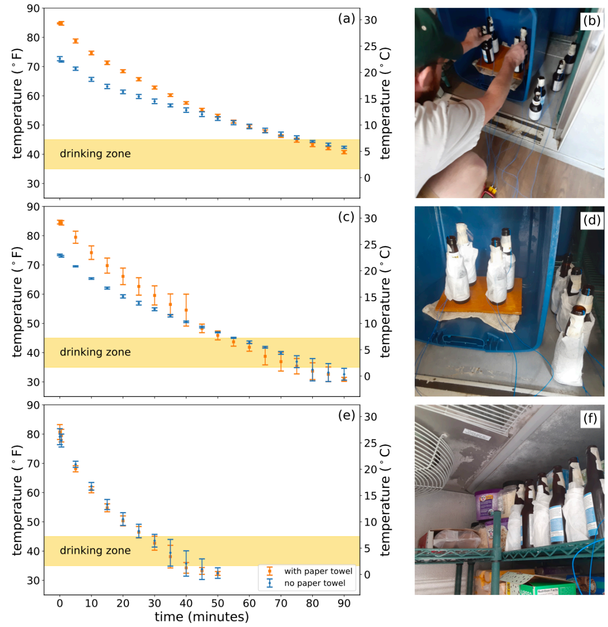

Fig. 1. Temperature measurements in the center of the bottle for three levels of advection. In the left column, the means and standard deviations of recorded temperatures for paper-towel-wrapped bottles are shown as orange squares and for non-wrapped bottles as blue points. The gold bar represents good drinking temperatures for beer. We conducted experiments in the following configurations: (a) beers placed in a bin to minimize advection, (c) beers outside of a bin, (e) beers near a fan. In the right column, we show images of each experiment.

In the left column, we see the steady cooling of the beers in each of our experimental conditions. For bottles in a bin (panel (a)) and next to the bin (panel (c)), the beers reach a good drinking temperature at the same time, even though the paper-towel-wrapped beers started warmer. This supports the hypothesis that the wet paper towel aids in cooling. In panels (c) and (e) we see the role of advection: beers cooled more quickly when exposed to circulating air from the fan at the top of the freezer. Advection mattered much more than paper towels; when the beers were placed close to the freezer fan (panel (e)), both the beers wrapped with wet paper towels and the beers that were not wrapped with wet paper towels cooled to a suitable drinking temperature in approximately 30 minutes, much more rapidly than did beers in the presence of little to no airflow.

Because the beers in our 0D experiments had different initial temperatures, we summarize the times required for beer to cool from 70°F $(21.1^{\circ}$C$)$ to 45°F $(7.2^{\circ}$C$)$ in each experimental condition in Table I. For the no- and low- advection environments, wrapping a beer in a wet paper towel reduces the time to cool the beer by about 25%. Overall, however, the most effective way to cool a bottle of beer was to increase the amount of air advection near the beer. When a beer was not wrapped in a wet paper towel, adding high levels of air advection reduced the cooling time by 69% compared to a non-wrapped beer in a bin. Similarly, placing a paper-towel-wrapped beer in high levels of air advection reduced the cooling time by 60% compared to a paper-towel-wrapped beer in a bin.

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paper towel	advection	time to cool 70°F (21.1°C) → 45°F (7.2°C) [min]
no	no	74.1
no	low	50.9
yes	no	57.0
yes	low	37.3
yes	high	22.7
no	high	23.0

Table I. Time for beers in 0D experiments to fall from 70°F (21.1°C) to 45°F (7.2°C). We used our mean cooling data to determine the time it took for each beer to reach 45°F (7.2°C).

B. Radial Beer Cooling

Our 0D measurements have suggested that a wet paper towel increases the cooling rate by a modest amount. The measurements alone, however, do not provide a physical picture of why this occurs and why advection considerably increases this rate. Thus, we performed a separate set of experiments with radial temperature measurements to gain additional insights. As before, experiments were performed with and without wet paper towels, and with different levels of advection. In these experiments, we compared the effects of no- and high-advection environments on cooling, and we used multiple thermocouples in and near each beer bottle. Thermocouples were placed in the center of each bottle and at the interfaces between materials (beer-glass, glass-paper towel, glass-air, paper towel-air). For the bottle not wrapped with a wet paper towel, we placed a thermocouple in the open air 4 mm away from the bottle. For each set of conditions, we measured temperatures once for a single beer.

We show our results as space-time plots in Fig. 2. The background colors were produced using contourf in matplotlib using 500 levels with our data. The solid black lines were made using contour in matplotlib. Results for beers in the no-advection environment are shown in the top row, and those for the high-advection environment, in the bottom row. In the left column, results for beers that were not wrapped are shown, and in the right column, results for beers that were wrapped are shown. Contours for good drinking temperatures are overlaid as solid black lines, and the glass portion of the bottle is represented between the two vertical lines. As expected, the new measurements made at the center of the bottle are consistent with the measurements discussed above in Sec. IIA. Note that a warm atmosphere forms outside the glass region at early times, as shown in the lower right of panel (a). This region cools slowly. In contrast, when advection is present, as in panel (c), the warm atmosphere is quickly replaced by substantially cooler air. Thus, the surface of the bottle is in constant contact with air at freezer temperature; without advection, the beer forms a warm atmosphere that slows cooling by reducing the temperature gradient. This basic phenomenon appears within the paper towel as well. In Sec. III, we use these measurements to validate our numerical results.

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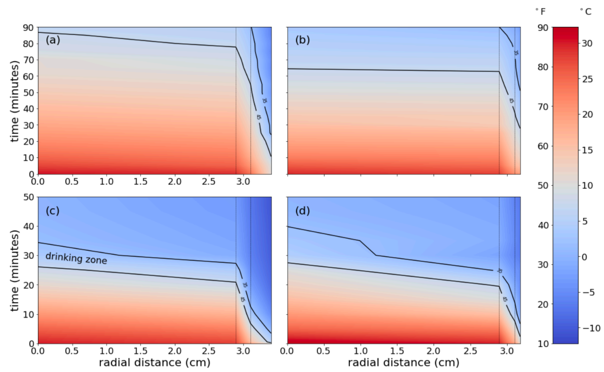

Fig. 2. Radial temperature evolution of cooling beers. Shown is the temperature evolution of beers in a no-advection environment (a) not wrapped and (b) wrapped, and of beers in a high-advection environment (c) not wrapped and (d) wrapped. The vertical lines denote the glass region.

C. Infrared Images of Cooling Beer

To explore the warm atmosphere that formed around the bottle further, we imaged the bottle in the infrared spectrum using an infrared camera (Hti HT-02, Tools for instrument, China). The infrared images captured by this camera are mapped to the visible spectrum such that they highlight differences in temperatures.

In a no-advection environment, the warm air surrounding the bottle will rise, and nearby cool air will replace the rising air. This air movement leads to natural convection currents, known as "Rayleigh-Bénard convection".[11] Depending on the relative values of the relevant parameters, such air movement could bring cold air from locations far from the beer, such as air adjacent to cold surfaces and/or blowing air in the freezer, next to the beer *much faster* than could thermal conduction alone.

Our experimental setup and images generated using the infrared camera are shown in Fig. 3. To visualize a cross-section of the heat flow, a cardboard plane was placed perpendicular to the bottle, as shown in panel (a) in the visible spectrum. In panel (b), which combines infrared and visible images, we see that the bottle is heating nearby materials, consistent with the warming near the bottle seen in Fig. 2. The warm plume rising above the bottle in panel (b) occurs because of convective heating and is consistent with Rayleigh-Bénard convection. In panel (c), which is a pure infrared image, overlaid red arrows show the direction in which warm air flows, and blue arrows indicate the directions in which cool air flows in to replace rising warm air. This air motion induces air currents that cool a beer more quickly than it would cool if the air were completely stationary.

These measurements concluded the physical experiments we performed in this study. In the next section, we compare our radial measurements with our numerical simulations.

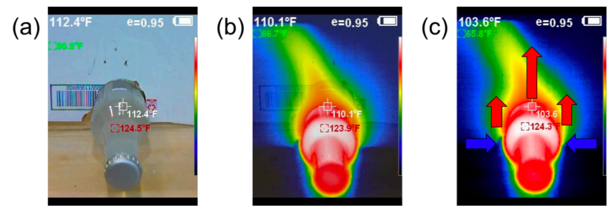

Fig. 3. Infrared images of a cooling beer. (a) We surrounded a beer with cardboard to examine how heat flows away from the beer, shown here in the visible spectrum. (b) An infrared image is overlaid on the visible image and shows both a radial conductive heating component and upward convective heating, which forms a plume. (c) A pure infrared image is shown, with red arrows indicating the upward flow of warm air, which draws cooler air toward the bottle, indicated by blue arrows.

III. Comparison of Numerical and Experimental Results

To gain additional insights beyond the experiments described above, we developed a theoretical model based on Fourier's heat law (more details are in the supplement),

$$\rho(r)c_p(r)\frac{\partial T(r,t)}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}r\left[\kappa(r)\frac{\partial T(r,t)}{\partial r}\right], \qquad (1)$$

that describes the beer, glass bottle, paper towel, and surrounding air through known parameters κ (thermal conductivity), ρ (density), and c_ρ (specific heat). Notice that the model's parameters are spatially dependent to account for the different materials in the experiment. Generally, these properties depend on the temperature and pressure of the material. However, for our models, we assumed that these thermodynamic properties are constant throughout our simulations as they vary little over the conditions in our experiments. The values we used are given in Table II.

	liquid water[12]	ethylm alcohol[12]	glass[13]	paper[12][14][15][16]	air[12]	beer[17]
$c_p\,[\mathrm{J/kgK}]$	4181.8	2438	870	1340	1007	4337.3
$\rho[\mathrm{kg/m^3}]$	998.21	790.5	2500	700 - 1150	1.161	977.7
$\kappa[\mathrm{W/mK}]$	0.5984	0.167	1.06	0.05	0.0262	0.57

Table II. Material properties. The specific heat capacity c_p, density ρ, and thermal conductivity κ are listed for the various materials used in our simulations. We list pure water and ethanol here as references for the values we used for beer. We included paper for general interest only as we assumed the paper towel was too dilute to affect the properties of water.

The thermodynamic properties of glass, paper (which we treat as wood), and air are easily found in the literature, but this is not the case for beer. Thus, in our simulations, we approximated beer as a 95% water-5% ethanol mixture. However, the thermodynamic properties of mixtures are not always trivially related to the thermodynamic properties of the components of the mixtures. Water-ethanol mixtures, in particular, are among the mixtures that display anomalies; both the specific heat and the thermal conductivity of such mixtures have positive slopes at low concentrations of ethanol, and these slopes become negative at higher concentrations of ethanol. Fortunately, high-resolution data for the thermal conductivity, heat capacity, and density of water-ethanol mixtures have been reported.[17] We interpolated these data to estimate the thermodynamic properties of a 95%water-5% ethanol mixture to inform our model of the thermodynamic properties of beer.

We approximated a wet paper towel wrapped around a bottle of beer as a thin layer of water surrounding the bottle. We made this choice because we believe that when saturated, the paper towel will act only as a scaffold that holds water in place, and that, moreover, the towel is too dilute to affect the properties of the water. Thus, we include paper in Table II for general interest only, as our model does not include the effects of paper beyond its use in holding water in place. (For example, this value would be the limiting value in a model in which all of the water evaporated, rather than freezing.)

Water's high specific heat relative to air suggests that wrapping a beer with a wet paper towel could cause it to cool more slowly, as more energy is required to cool the water. Moreover, air's low thermal conductivity implies that heat cannot be conducted away from the beer very quickly. Thus, looking solely at the properties of the individual materials involved, we might expect that wrapping a beer in a wet paper towel would not help it to cool faster. However, as we have seen in our physical experiments, air movement, and evaporation are important and are not directly captured by the individual material properties.

Beyond the material properties, we needed to impose several physical constraints and choose our grid spacing. Specifically, we required that the widths of each material in our simulation match those in our physical experiments. We measured the widths of the various materials that were used in our experiments, and we list these measurements, together with the grid spacing we used, in Table III. We chose to use 80 cells per material in each numerical simulation, as this number of cells showed good convergence compared to that seen when using a higher number of cells. Using the values in Tables II and III, we are now able to initialize the domain and model parameters to simulate our experiments.

	beer	glass	paper towel	air
width [cm]	5.785	.215	.073	20.32
grid spacing [cm]	.0723125	.0026875	.0009125	.254

Table III. Physical widths and grid spacing for each material, using 80 cells per material.

Numerical solutions of Eq. (1), a partial differential equation in cylindrical coordinates, were found using a finite-volume and Radau method. The initial conditions for each simulation were an air temperature of -21.1°C (-5.98°F) and a constant temperature throughout the non-air materials; for each simulation, the temperature of the non-air materials was set to the initial temperature of the beer in the experiment being modeled. Each simulation considered either wrapping a beer in a wet paper towel or not, and with either high advection or no advection. For experiments performed in the bin (no advection), we used a Dirichlet boundary condition that held the edge of the domain, chosen to be at the bin wall, at -21.1°C (-5.98°F). Equation (1) does not model advection in the air, and Fig. (3) shows that natural convection occurs in the air. We approximate these phenomena by employing a convective boundary condition[18] (Robin boundary condition) next to the last solid material (glass or paper towel) in the domain. We fit the heat transfer coefficient present in the convective boundary condition using our 0D data from Sec. IIA. Each simulation was run for 1.5 hours of simulated time. Additional details are given in the supplement.

We compare numerical solutions of Eq. (1) in a high- and no-advection environment in Fig. (4). Our numerical results are shown as solid lines, and our radial measurements from Sec. IIB as Xs. The top panels show results for wrapped beers and the bottom panels show non-wrapped beers. The left panels show results for the high-advection environment. The middle panels show results for the no-advection environment without natural convection and the right panels show the no-advection environment with natural convection.

In Fig. (4), we see our numerical results slightly underpredict cooling; nonetheless, they agree well with our experimental data in the high-advection environment. In the no-advection environment, our numerical model performs very poorly when we implement a Dirichlet boundary condition at the edge of the bin that does not allow for air to move. This poor performance is rectified when we instead use a convective boundary condition at the edge of the bottle or paper towel. This reveals two important ideas. First, the better performance provides additional evidence of natural convection occurring in the bin as discussed in Sec. IIC. Even when we block air flows from the fan, using a bin, our data more closely resembles a model that includes convection. Second, we see the importance of choosing the correct boundary conditions in a model. While both the Dirichlet and convective boundary conditions may seem reasonable to apply to our problem, only one produces results consistent with our data.

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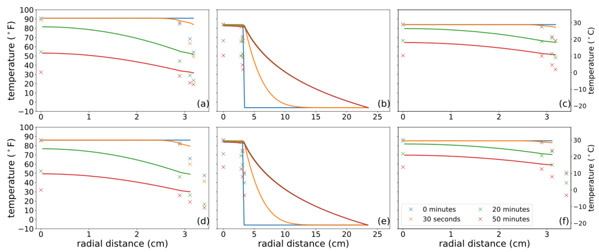

Figure 4. Comparing simulation results and experimental data. The left panels show results in the high-advection environment. The middle panels show results in the no-advection environment with a Dirichlet boundary condition at the edge of the bin, and the right panels show results in the no-advection environment with a convective boundary condition at the edge of the last solid material. Solid lines are results from our simulations, while Xs are data from our experiments. We show comparisons at different times in different colors. Our simulation results agree well with our data in the high-advection case and when we use a convective boundary condition in the no-advection case. These results demonstrate the importance of boundary conditions and provide additional evidence of natural convection in our experiments performed in a bin.

IV. Conclusions

Our goal was to develop a scientific, yet broadly approachable, approach to answering the question of whether wrapping a warm beer (or other beverage) in a wet paper towel before putting it in the freezer helps to cool the beer, compared to not wrapping it in a wet paper towel. To achieve this goal, we performed experiments that generated data that were gathered in a systematic way. Measurements were made

with and without a wet paper towel and with three levels of air advection. We then generated numerical solutions to the heat equation, and we compared our numerical results directly with our radial measurements at different times. Our main conclusion is that wrapping a wet paper towel around a beer bottle speeds its cooling, but not substantially; the wet paper towel offers only a 23% reduction in cooling time. However, air advection reduces the cooling time by 60% to 70%.

Perhaps these results are expected, to some, when looking at the thermal conductivities of the materials alone (Table II). Air, with its low thermal conductivity compared to glass and beer, suggests that heat cannot be conducted away from the beer quickly. By continuously replacing the insulating air with new cool air, one would expect to decrease the time it takes to cool a beer. Here we quantify this decrease in cooling time. The effect of the wet paper towel is not as clear when examining the thermal conductivities alone. Again, we quantified the effect of adding a wet paper towel in a controlled environment.

One of the conclusions of our work is that many details matter. This observation could help explain the differing results and opinions across the internet about the viability of the wet-towel method.

For example, the most important physical process involved in cooling a beer appears to be air advection, independent of a wet towel. The fastest way to cool a beer is to put it next to the incoming cold air in a freezer and it stands to reason that occasionally rotating the bottle to induce mixing within it would speed cooling further. Convection within a beer itself may be induced by vibrations, which could occur to different extents in different freezers.

We provide ideas for future experiments in the supplemental material. Most importantly, we hope that we have demonstrated an approach that can be used to solve unrelated everyday problems using theory, experiments, and computation, similar to those used to shed light on processes involved in baking cakes,[7] sinking bubbles in Guinness beer,[8] and operating a French press.[9]

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Declarations

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