On the brewing of tea

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This study is motivated by the search for an exceptional brew for the Empire. An American tea tycoon was contracted to provide outstanding tea leaves and a team of guinea pigs exploited to brew them and assess the result. Major issues were faced such as the lack of knowledge of the pigs and the unavailability of laboratory equipment. Both were resolved satisfactorily: the tycoon provided brewing protocols and the pigs used inventiveness to substitute for the desired equipment. Findings on a specific type of oolong tea are reported for two different types of preparation: cold brewing and hot brewing. The results are novel and invaluable to the Empire. They will also be relevant to tea drinkers as well as those who are not yet such.

I. INTRODUCTION

Tea is a British specialty that is often overlooked. Foreigners associate British tea with breakfast tea. They purchase low quality British tea and use it as a functional beverage to enhance their alertness rather than for their effect on tastebuds. Consequently, when non-Britons purchase delicious tea, they often choose Chinese tea, overlooking the best English beverages. Incidentally, Britons are not exempt from misjudgment either when it comes to tea. When they want to taste good foreign tea for a change, more often than not, Britons choose bad Chinese tea, lured by the price or simply confused by the descriptions. After all, Britons are not very fond of studying Mandarin: only 1,500 students took Chinese or Mandarin at undergraduate or postgraduate level during the academic year 2010/2011 [1]. Regardless, the reputation of British tea extends to the Galaxy and the Empire is funding a research program in the UK to discover outstanding brews.

To provide the best analysis, the Empire has contracted a partnership with an American giant of the tea industry and a number of knowledgeless tasters. The former acted as a consummable provider and advisor on the procedurial side carried out by the latter. Following his recent visit to British tea companies, the American tycoon decided to keep all the British tea for himself and provide us with Chinese tea instead [2]. We have therefore tested Chinese tea, but have done our best to keep a major British component in this study by brewing the tea with British utensils in our London premises.

This paper is structured as follows: in section II, we introduce the guinea pigs who put their life in jeopardy to report their findings, the American magnate who provided the consummables, the independent observer and brain behind this study and the oolong tea that was used. The next section is devoted to the protocol, as advised by the influential leaf provider. Section IV reports on the brewing experiments and tasting. The paper terminates with a short conclusion.

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II. THE PROTAGONISTS

For this study, 1,071 testers responded positively to the call from the Empire. Unfortunately, most of them changed their mind upon learning that the tea to be tested was not British but Chinese. Only two people remained interested, none of them of British nationality. We will refer to them as guinea pigs [3].

First, Ludmiła Rozmarynowska (LR, see figure 1(a)), an Australish [4] number wizard. She likes cheese and Scarlatti, and hates having to wedge doors open with scissors. She proceeded to this study alongside Cédric Beaume (CB, see figure 1(b)), an Atlantic [5] nerd. He likes duck ponds and dancing the macarena when leaving his flat, and hates the expression "breadth and depth". It is important to mention what might be wrongly perceived as a shortcoming in this study. None of the guinea pigs is British despite one of them having lived in the United Kingdom for about 10 years. We assure the reader that care has been taken to provide the most accurate analysis in the British sense. In particular, pinkie raising and slurping were generously applied during tasting.

The guinea pigs were provided with the consumables by Benjamin Ponedel (BP, see figure 1(c)), an American tea tycoon. He likes tea and whining and hates everything else, a happy coincidence as he can then whine about it and enjoy himself in the process.

Lastly, the man behind this study, Lord Vader (Darthy [6], see figure 1(d)), remained present all along the process to make sure all violations to the protocol were reported and to enforce the objectivity of the testers. He is the Imperial Supreme Commander, likes his cape and climbing on the back of people and hates the bitterness of life without Padmé. After many long years of attempting to cover up the aforementioned bitterness with coffee, Darthy has decided to search for a new brew. In addition to soothing his life, he hopes that the perfect brew will help convince his son to join him in heading the Imperial Aerospace Department. To that end, he landed his spaceship in London, the city that enjoys the best reputation for tea in the Galaxy. From there, he contracted the most-read still-living tea author, BP, and looked for local tasters, building up the aforementioned team.

FIG. 1. (Color online) Top left: Ludmiła Rozmarynowska back home. Top right: Cédric Beaume well-prepared for his first brewing. Bottom left: Benjamin Ponedel visiting his favorite tea producer. Bottom right: Lord Vader sipping bitter coffee in his headquarters.

The tea that was provided is Chinese and belongs to the family of oolong teas known as *Tieguanyin* or *Iron Goddess* tea. Such teas are very reputable [7] but the name can be misleading as it encompasses light roasted versions with flavors of green tea and heavily roasted ones with black tea flavors. We were provided with a red lustre sachet (see figure 2) of the former kind that we will refer to as *JD-1502*.

III. THE PROTOCOL

For the leaves not to be wasted and reach the quintessence of Chinese tea, BP provided very careful instructions [8]. These instructions concern two different types of brewing methods: cold and hot brewing. While it appears that the success rate of cold brewing is higher, it rarely matches hot brewing in terms of outright quality when perfectly executed. Given the level of experience of the guinea pigs, BP kindly advised "I actually think it might be best for you to cold brew the tea. [...] You cannot mess up cold brewing."

FIG. 2. (Color online) Sachet of Tieguanyin tea, JD-1502, used for this experiment. The left (resp. right) panel shows the front (resp. back) of the sachet.

A. Cold brewing

We report here the instructions provided by BP:

Place leaves in teapot.
Pour in 1,656mL to 2,129mL of filtered water [9].
Put teapot in refrigerator overnight ($\sim$ 8 hours).
Enjoy.

Some other comments were provided. In particular, it is possible to obtain a stronger tea via using less water. It follows that, if the tea is too strong, it is possible to add water to convenience. Note: this cannot be done when hot brewing.

Such cold brewed tea produces smoother tea than hot brewing and is a great way to keep drinking tea during the hot months [10]. BP enthusiastically added "This is the real way to make iced tea." It also has the advantage of lasting a couple of days once brewed, unlike hot brewed beverages. A major downside of cold brewing is that it does not allow to extract some of the benefits of hot tea [11].

B. Hot brewing

Again, we start with BP's instructions:

Raise filtered water to between 75°C and 85°C.
Place leaves in teapot.
Pour in water to rinse leaves.
Dump rinsing water out.
Cover teapot.
Let leaves uncurl for one minute.
Pour in 237mL to 355mL of water [12].
Taste tea every 30s until desired taste is reached.
Dump tea out into different teapot.
Enjoy.

It is important to note that the brewing time should not exceed 2min and is typically closer to 1min. Brewing with water that is not sufficiently hot will increase the duration of this process for optimum taste. Importantly, tastes vary from individual to individual and some might like a longer brew than others.

The tea produced this way is more bitter than using the cold brewing protocol and there is a real risk of failing the brew. Several causes can lead to failure, notably scalding the tea, i.e., brewing it with too hot water. Other mistakes can easily be avoided such as oversteeping by using a second teapot to dump out the brewed tea and avoid prolonged contact between the leaves and the tea. Any of these mistakes increases the bitterness of the brew to an undesirable extent. As an indicator of the difficulty of this brewing mode, let us mention that BP himself fails about 30% of the time when he does not pay attention [13]. He advised that optimal hot tea requires to practice brewing more than once, politely concluding that "[the guinea pigs] might not have enough patience or enough tea."

C. Analysis

When it comes to the different ways of brewing tea, previous work has established a very important indicator. It is formulated in terms of a Yummy function Y [14], named as a tribute to the tea pioneer Yummy Wang, aka Ken Obi. Note that in the obscure work by Ponedel, this function is also called the happiness function [8, 15]. Twinings and Tetley [14, 16, 17] found that this function is strongly correlated with a dimensionless number, the Brewing number B. The calculation of B is beyond the scope of this paper and we refer the reader to the excellent review by Lipton [18] for a detailed explanation. In short, $B = 0$ for a perfect brew and departs from 0 monotonically as the brewing quality decreases.

Figure 3 shows the differences between the Yummy function associated to the cold brewing process and that associated with the hot brewing one. These established results indicate that the Yummy function generated by hot brewing peaks sharply for perfect brews to values approaching 0.9 while it only approaches 0.4 for cold brewed teas. Away from perfection, the hot brew Yummy function decays faster and above $B \approx 0.63$, cold brewed teas are more enjoyable. Since the integrals of both functions on the real line tend to 0.5, both types of teas are theoretically equally enjoyable. However, hot brewing becomes a better choice for an experienced brewer as values of B smaller than 0.63 are more often reached.

We want here to report an inconsistency in the theory: the brewer is not a randomized machine, i.e., they do not generate randomly distributed B between 0 and ∞. In particular, they aim at brewing tea perfectly. We can thus expect that they will generate a distribution for B that is close to a Gaussian centered on 0. Integrating over the resulting probability density function we discover that hot brewing provides much better results than cold brewing. We are surprised that this theory has not yet been challenged.

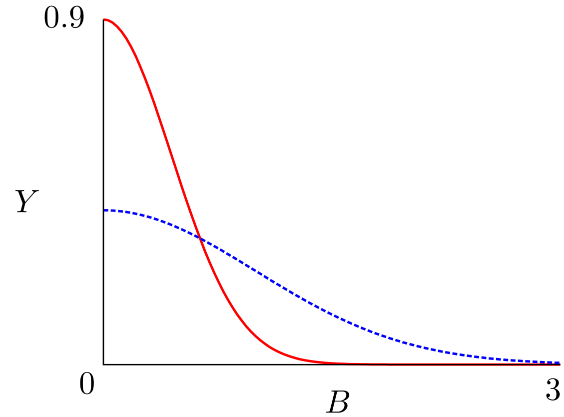

FIG. 3. (Color online) Yummy or happiness function Y as a function of the Brewing number B for cold brewing (blue) and hot brewing (red). After Lipton [18].

FIG. 4. (Color online) Tearing the JD-1502 sachet revealed a second sealing bag containing the leaves.

IV. BREWING RESULTS

To avoid deciding between cold and hot brews, we decided to split the leaves into two samples, one for cold brew and one for hot brew. The opening of the JD-1502 sachet was performed on Friday, October 2, 2015 at 8:11pm, revealing a doubly sealed leaf sample (see figure 4). The sachet was then opened and smelled. It was very aromatic, a well-balanced and pleasing scent emanated from the leaves. Upon smelling it, CB noted "it doesn't smell of paper, like usual tea" and smelled again a couple of times. The smell test passed, two equal-sized samples were formed, one for the imminent cold brew and the other one for resealing in view of a subsequent hot brew. The original resealing attempt by CB, using a knife blade heated in boiling water, failed due to the misjudgment of

FIG. 5. (Color online) Half of the leaves were resealed using wrapping film. Note: the content of the bag is JD-1502. It passed customs successfully and is by no means illegal.

FIG. 6. (Color online) Left: pouring water into the teapot: the determining step for the cold brew. Right: leaves brewing in the teapot, gravity points away from the reader.

the melting point of the wrapping plastic. Fortunately, on an idea of LR, a generous amount of wrapping film from the brand *M savers* and presented in a roll of 60m $\times$ 300mm approximately was used at 8:21pm to preserve the leaves as shown in figure 5.

A. Cold brewing

The cold brewing experiment was run on Friday, October 2, 2015 starting at 8:04pm. The use of filtered water was not made possible by the absence of a filtering device in our laboratory. Instead, we used the high-quality *Evian, eau minérale naturelle* water which came in a 2L bottle. Their slogan, "Live young", does not prevent its use for tea and seemed to make our guinea pigs enthusiastic.

As half the leaves were used, approximately 0.85L of Evian water was measured at 8:10pm and set aside. The JD-1502 leaves were placed in the internal strainer of a red porcelain teapot and, at 8:17pm, CB poured the measured water onto them (figure 6). Curiosity led the guinea pigs to only cover the teapot at 8:23pm in an operation performed by LR. The tea was then placed into a fridge by the latter at 8:24pm where it spent the night, between a bottle of semi-skimmed milk and a jar of cerises noires griottes cuit au chaudron [19].

Tasting took place on Saturday, October 3, 2015 at 10:24am, roughly 50820s after brewing, which corresponds to approximately 1.76 times the advised resting time of 8 hours. CB opened the fridge and took the teapot out. It was cold but remained red. Curiosity was at its paroxism and, by 10:25am, the guinea pigs unavoidably opened the teapot to examine the brewed liquid. Immediatly, the smell surprised us: it smelled of lemon, maybe of washing up liquid. At first, this is a rather comforting observation, indicating that the apparatus has been well-washed before the experiment. However, the guinea pigs were scared: drinking washing up

FIG. 7. (Color online) Resulting cold brewed tea being poured into a teacup. Note that the blur of the picture is the result of the experiment being carried out in the morning. No one should be required to work at this ungodly hour.

liquid flavored tea on an empty stomach was not an experienced to which they looked forward. Additionally, the tea smelled of fridge, a very undescribable scent, encompassing that of French cheese and surströmming [20]. At 10:26am, CB poured the tea into teacups, as shown in figure 7. Both LR and CB were surprised to notice how light the color was, a "disappointing yellow" for CB. Slurping ensued at 10:27am, see figure 8. Politely, LR waited for CB to give away his impression. He did not take long to shout "Holy Duck, this is super cold!" a statement immediatly upheld by LR who added "Maybe in California, they drink it cold?", referring to the location of BP's headquarters. The guinea pigs then decided to leave the tea aside for it to warm up.

At about 10:35am, the tea reached a tastable temperature and the experiment resumed. It appeared surprising, according to LR, that the tea had no inverted sedimental layer. A number of comments emerged from this tasting session which are summarized in the following sentences.

FIG. 8. (Color online) Asleep LR (left) and CB (right) slurping cold brewed tea. The loudest slurp contest was won by the latter.

FIG. 9. (Color online) Oversteeped tea. See figure 7 for color comparison.

The tea had the deceivingly strong flavor of green tea in spite of its nature and the light color of the brew and the red color of the packet. It was neither bitter nor aggressive but rather soft and full-bodied. In the end, the tea received LR and CB's utmost praise and a second cup was poured for private degustation.

As pointed out by BP, cold brewed teas can be kept for two days. We decided to keep the rest for later. The teapot was placed in a cupboard so as not to cool the beverage down too much. On Sunday, October 4, 2015 at 6.48pm, the tea was taken out of the cupboard for the ultimate degustation. Very surprised, we noticed how strong the color became (figure 9). Immediate tasting revealed a very bitter and strong tea, undrinkable. Slurping was followed by spitting, another British tradition often performed in football stadiums. We concluded that the tea became oversteeped and that BP ommitted to mention in the protocol that the leaves had to be removed from the teapot once the night had passed. In spite of its simplicity, the guinea pigs managed to fail the cold brew.

FIG. 10. (Color online) Layout of the heating apparatus for the hot brewing experiment: the water was poured out of the bottle into a pan. The pan was then pushed onto the heating stove (in red, on the left) until boiling. The desired amount of water was then transfered into the measuring cup (behind the bottle) until cooled down to the desired temperature.

B. Hot brewing

Some delays occurred between the cold brewing and the hot brewing experiments partly due to the start of the viral season in London and a battery issue that left Darthy speechless. Fortunately, our team took good care of the leaves after cold brewing. They were kept safely and in the best conditions: the JD-1502 leaves were wrapped tightly in film and placed in an overhead cupboard maintained at room temperature.

The hot brewing experiment started on Saturday, October 31, 2015, less than a month after the cold brewing one and the cold epidemic. The leaves were unwrapped at 4:57pm in an operation that lasted two long minutes. Let us here point out that the length of time it took the guinea pigs to free the tea leaves is a proof of the quality of their preservation. By 4:59pm, the leaves were out again for another smell test: JD-1502 behaved similarly to October 2, 2015, they did not lose any scent and the initial smelling triggered a few more smellings followed by laudatory noises before the experiment could resume.

A different, cheaper water was used this time. It was branded *Sainsbury's*, read *still Scottish mountain water* and was sold in bottles of 0.5L. Although we only used half of the leaves, we decided to depart from BP's instructions. His advice was to use 237mL to 355mL of water for the whole leaf sample but dividing the quantities by 2 would have produced too little tea. In addition, the shape of the available teapots would not allow such a small quantity of water to cover all the leaves and would lead to suboptimal brewing. We decided to use 250mL of liquid, remaining acceptably close to the top of the advised range (119mL to 177mL) while still making it possible to brew two decent cups. One bottle of 0.5L was opened and its content poured in a pan at 5:06pm (figure 10). The pan was placed on a stove on high heat to

FIG. 11. (Color online) Strainer used for hot brewing shown during the placement of the leaves into it. This strainer consists of two hemispheres assemblable with the help of a clip. It comes with a chain (left of the picture) terminated by a hook (not shown) that is useful for attaching it to a glass or teapot. We have here used the hook with the mouth of the teapot as shown in figure 12.

FIG. 12. (Color online) Hot brewing of JD-1502. Note that the chain of the strainer can be seen and its hook is attached to the mouth of the teapot for easy removal.

make the water boil as quickly as possible. In the meantime and in anticipation of the following brewing steps, we realized that the strainer used in the cold brewing experiment was not suitable: it does not touch the bottom of the teapot so would not allow all of the leaves to soak. To cope with this unforeseen issue, we chose to use the replacement strainer shown in figure 11 and placed the leaves in it at 5:08pm.

The water started boiling at 5:11pm. A quick calculation, overviewed in Appendix A, was a priori carried out to determine the time it would take the fluid to cool down from boiling temperature (100°C) to the desired temperature of 75°C to 85°C. Unfortunately, this calculation failed and we had to play it by ear. A cooling time of 30s was agreed without argument due to the rather large range of acceptable temperatures. Half of the water was poured into a measuring cup (see figure 10) for cooling. The rinsing step was carried out by LR: after a 30s cooling period, she poured some of the water on the leaves before quickly dumping it out in the sink. At 5:12pm, the teapot containing the rinsed leaves was covered to allow them to uncurl for about a minute. While the leaves uncurled, the unused water was poured back into the pan and reheated. When the second boiling was reached, at 5:13pm, 250mL of boiling water was measured in the cup and let to cool for 30s before commencing the brewing.

Proper brewing started at 5:14pm when LR gently poured the content of the cup into the teapot and covered it, as shown in figure 12. To ensure that the brewing time is determined consistently, LR was chosen as the unique taster while CB recorded her impressions. The first tasting occurred at 5:15pm, after one brewing minute. The brew was very light colored, mainly yellow. It was very pleasant to taste, very similar to green tea but not strong enough so the guinea pigs decided to prolong the brewing.

The second tasting took place 30s later, in accordance with BP's instructions. The brew had a darker color with a very similar taste, albeit sensitively stronger. Out of impatience and perhaps fear of oversteeping the tea, the guinea pigs decided to stop the tasting there and enjoy the tea. For the sake of transparency, we recognize that the tasting time, together with the discussion time that followed extended the brewing time in a considerable way, especially given how short the overall process is. We estimate the actual brewing time (between the moment the teapot is filled and that at which the leaves are removed from the teapot) was between 120s and 150s. This is in accordance with BP's instruction that mentioned that the tea should not brew for longer than 2 minutes but that if the temperature of the water is slightly lower, it might be extended a bit.

LR poured an equal quantity of tea into two cups at 5:17pm, noticing that it was very nicely colored (figure 13). The decision to use 250mL of water proved to be a good idea: there was just enough tea remaining after the tastings to brew two reasonable cups. Conversely, whether using a different quantity would have changed the taste of the beverage or not remains an open question.

The degustation started at 5:19pm. Tasting was immediatly followed by heavy silence revealing how hard it was for the guinea pigs to find words describing their first impressions. They broke the silence in unison: "it's amazing!" As they took a slurpy second sip, their judgment became more accurate, but still similar in substance: the tea was not bitter but very smooth. LR noted: "it is not watery", adding: "it is clearly brewed, yet not aggressive." After a few stuttering moments, CB successfully articulated: "it doesn't feel like a mix of flavors but rather one very nice flavor." and was left very satisfied, as confirmed by figure 13, right panel. In other words, hot brewed JD-1502 is well-rounded and has a lot of character while not being aggressive. Unfortunately, none of the guinea pigs was able to remember the taste of the cold brew for comparison.

FIG. 13. (Color online) Left: pouring of the hot brewed tea into the cups. Middle: LR degusting the beverage while practising pinkie raising. Right: CB, proudly holding the cup of JD-1502, is a happy taster.

FIG. 14. (Color online) JD-1502 leaves after hot brewing. The leaves are green with rare spots of brown, nicely cut and have uncurled and expanded greatly.

The tea was quickly finished and, at 5:29pm, we decided to inspect the leaves post brewing. They have a deep green color and smell of tea.

V. CONCLUSIONS

In this paper, we reported on a double experiment. We were provided with tea leaves of a particular, oolong, kind and given instructions to test them. We tried two kinds of brewing methods: cold and hot brewing. The former produces an enjoyable beverage, appropriate for the summer. It is difficult to spoil, but we managed to oversteep the leaves for the second degustation. On the other hand, the hot brewing technique is difficult to execute but we managed to obtain an excellent beverage.

Due to the high level of specificity of the given protocols, we have not been able to meet the exact requirements set by our provider. In particular, we were not in possession of gloves, thermometers, scales, water filter, etc. Upgrade of our equipment will be made upon further consummable delivery.

Despite the shortcomings reported in this paper, the brew turned out to be satisfactory and received full approval from Darthy. A motion has been sent to the Imperial Senate for the selection of these brews as official beverages of the Empire.

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APPENDIX: MODELING OF WATER COOLING

We consider the cooling of boiling water in a circular container at room temperature and try to determine how much time the fluid has to sit in the container before reaching a temperature of 75°C to 85°C.

Problem formulation

The domain of interest for the calculation is the cylinder $r^* \in [0, L^*]$ where $r^* = 0$ is the center of the cylinder, $r^* = L$ is the edge, $\theta^* \in [0, 2\pi]$ is the angle in a horizontal plane from an arbitrary horizontal segment crossing $r^* = 0$ and $z^* \in [0, h^*]$ is the height, $z^* = 0$ indicating the bottom of the cylinder and $z^* = h^*$ the surface of the fluid.

The fluid is considered at rest so that the only physical phenomenon at play is diffusion. The dimensional heat equation for this problem therefore reads:

$$\partial_{t^*} T^* = \kappa^* \nabla^{*2} T^*, \tag{1}$$

where t^* is the time, T^* is the temperature and $\kappa^* = 1.43 \cdot 10^{-7} \mathrm{m}^2 \cdot \mathrm{s}^{-1}$ is the thermal diffusivity of water (note that for the sake of simplicity, this value is taken at room temperature and we do not take its dependence on temperature into account here). Hereafter, dimensional quantities are indicated with a star superscript. Equation (1) is accompanied with the following boundary conditions:

$$\begin{aligned} \partial_{r^*} T^* &= 0 && \text{at } \mathrm{r}^* = 0, && (2)\\ \max(\mathrm{T}^*) &= \mathrm{T}^*_{\mathrm{boil}} && \text{at } \mathrm{t}^* = 0, && (3)\\ T^* &= T^*_{atm} && \text{at } \mathrm{r}^* = \mathrm{L}^*, && (4)\\ T^* &= T^*_{atm} && \text{at } \mathrm{z}^* = 0, && (5)\\ T^* &= T^*_{atm} && \text{at } \mathrm{z}^* = \mathrm{h}^*, && (6) \end{aligned}$$

where $T^*_{boil} = 100°\mathrm{C}$ is the boiling temperature and $T^*_{atm} = 20°\mathrm{C}$ is the room temperature. The first boundary condition is necessary to enforce the axisymmetry of the solution. The second boundary condition indicates that at the start of the experiment, the hottest fluid parcel is at boiling temperature while the remainder of the boundary conditions impose continuity of the temperature field across the edge of the domain and within the room. Equation 1 can be expressed as:

$$\begin{aligned} \partial_{t^*} T^* &= \kappa^* \left(\frac{1}{r^*} \partial_{r^*} (r^* \partial_{r^*} T^*) + \frac{1}{r^{*2}} \partial^2_{\theta^*} T^* + \partial^2_{z^*} T^* \right) \\ &= \kappa^* \left(\frac{1}{r^*} \partial_{r^*} (r^* \partial_{r^*} T^*) + \partial^2_{z^*} T^* \right), \end{aligned} \tag{7}$$

after imposing the axisymmetry through $\partial_{\theta^*} \equiv 0$.

We nondimensionalize the problem in the following way. The time-scale of the problem is $\tilde{t} = 1\mathrm{s}$ and we write the dimensionless time as $t = t^*/\tilde{t}$. We proceed in the same way for distances using $L^* \approx 10^{-1}\mathrm{m}$ as the characteristic length-scale: $r = r^*/L^*$, $z = z^*/L^*$, $h = h^*/L^*$. Temperature is first reset linearly in such a way that room temperature corresponds to zero and then nondimensionalized using $\tilde{T} = 1°\mathrm{C}$ as temperature scale: $T = (T^* - T^*_{atm})/\tilde{T}$. Equation (7) becomes, in its dimensionless form:

$$\partial_t T = \kappa \left(\frac{1}{r} \partial_r (r \partial_r T) + \partial^2_z T \right), \tag{8}$$

where $\kappa = \kappa^* \tilde{t}/L^{*2} = 1.43 \cdot 10^{-5}$. The boundary conditions now read:

$$\begin{aligned} \partial_r T &= 0 && \text{at r} = 0, && (9)\\ \max(\mathrm{T}) &= \mathrm{T}_0 && \text{at t} = 0, && (10)\\ T &= 0 && \text{at r} = 1, && (11)\\ T &= 0 && \text{at z} = 0, && (12)\\ T &= 0 && \text{at z} = \mathrm{h}, && (13) \end{aligned}$$

where $T_0 = (T^*_{boil} - T^*_{atm})/\tilde{T}$ and $h = h^*/L^*$.

Temperature profile

Equation (8) is to be solved using variable separation. We pose $T(r, z, t) = f(t)\, g(r)\, l(z)$ and introduce the derivatives $f'(t) = \partial_t f(t)$, $g'(r) = \partial_r g(r)$ and $l'(z) = \partial_z l(z)$. Equation (8) yields:

$$f'\, g\, l = \frac{\kappa}{r}\, f\, g'\, l + \kappa\, f\, g''\, l + \kappa\, f\, g\, l'', \tag{14}$$

which, upon dividing by $\kappa\, f\, g\, l$ becomes

$$\frac{f'}{\kappa\, f} = \frac{g'}{r\, g} + \frac{g''}{g} + \frac{l''}{l}. \tag{15}$$

We note that the left-hand-side of equation (15) only depends on t while its right-hand-side only on r and z. The following problem can then be equivalently formed:

$$\frac{f'}{\kappa\, f} = -k, \tag{16}$$

$$\frac{g'}{r\, g} + \frac{g''}{g} + \frac{l''}{l} = -k, \tag{17}$$

with $k > 0$ so that f, and thus T, relaxes with time.

The solution of equation (16) is:

$$f(t) = A e^{-k\, \kappa\, t}, \tag{18}$$

with A to be determined. We note that equation (17) can be rearranged as follows:

$$\frac{g'}{r\, g} + \frac{g''}{g} = -\frac{l''}{l} - k, \tag{19}$$

where the left-hand-side only depends on r while the right-hand-side only depends on z. In a similar way as for system (16), (17), the following problem can be written:

$$\frac{g'}{r\, g} + \frac{g''}{g} = -m, \tag{20}$$

$$-\frac{l''}{l} - k = -m, \tag{21}$$

where $m > 0$.

Equation (20) can be recast into:

$$s^2\, \bar{g}'' + s\, \bar{g}' + s^2\, \bar{g} = 0, \tag{22}$$

by setting $s = \sqrt{m}\, r$ and $\bar{g}(s) \equiv g(r)$. The solution writes in terms of Bessel functions of first kind, J_0, and of second kind, Y_0:

$$\bar{g}(s) = B\, J_0(s) + C\, Y_0(s) \tag{23}$$
$$\Rightarrow \; g(r) = B\, J_0\left(\sqrt{m}\, r\right) + C\, Y_0\left(\sqrt{m}\, r\right), \tag{24}$$

where B and C are to be determined. Note that defining $m < 0$ would have led to imaginary arguments for the Bessel functions.

Equation (21) can be rewritten into:

$$l'' + (k - m) l = 0, \tag{25}$$

and is solved by:

$$l(z) = D\, e^{i\sqrt{k-m}\, z} + E\, e^{-i\sqrt{k-m} z}, \tag{26}$$

where D and E are to be determined.

The general form of the temperature field reads:

$$T(r,z,t) = e^{-k\,\kappa\, t}\left[K_1\, J_0\left(\sqrt{m}\, r\right) + K_2\, Y_0\left(\sqrt{m}\, r\right)\right] \ldots$$
$$\ldots \left(K_3\, e^{i\sqrt{k-m}\, z} + K_4\, e^{-i\sqrt{k-m} z}\right), \tag{27}$$

where $K_1 = AB$, $K_2 = AC$, $K_3 = AD$ and $K_4 = AE$.

Boundary condition (9) implies that $K_2 = 0$ and boundary condition (12) yields $K_3 = -K_4$. Solution (27) then reads:

$$T(r,z,t) = K\, e^{-k\,\kappa\, t}\, J_0\left(\sqrt{m}\, r\right)\, \sin\left[\sqrt{k-m}\, z\right], \tag{28}$$

with $K = K_1 K_3 / 2$.

Boundary condition (11) leads to $J_0(\sqrt{m}) = 0$, which implies that $\sqrt{m} = b \approx 2.4$, which is the first root of the Bessel function J_0. Boundary condition (13) yields:

$$\sin[\sqrt{k-m}\, h] = 0$$
$$\Rightarrow \quad \sqrt{k-m}\, h = \pi$$
$$\Rightarrow \quad k = \frac{\pi^2}{h^2} + b^2. \tag{29}$$

The temperature profile now reads:

$$T(r,z,t) = K\, \exp\left[-\left(\frac{\pi^2}{h^2} + b^2\right)\kappa\, t\right]\, J_0\left(b\, r\right)\, \sin\left(\frac{\pi}{h}\, z\right), \tag{30}$$

The maximum temperature is reached at $r = 0$, $z = h/2$ and $t = 0$. Boundary condition (10) thus gives $K = T_0$ and the fully-resolved temperature profile in the containter is:

$$T(r,z,t) = T_0\, \exp\left[-\left(\frac{\pi^2}{h^2} + b^2\right)\kappa\, t\right]\, J_0\left(b\, r\right)\, \sin\left(\frac{\pi}{h}\, z\right). \tag{31}$$

The temperature profile at $t = 0$ is shown in figure 15. The temperature is maximum at the center of the domain and decays away from its center to reach room temperature at the edges of the domain.

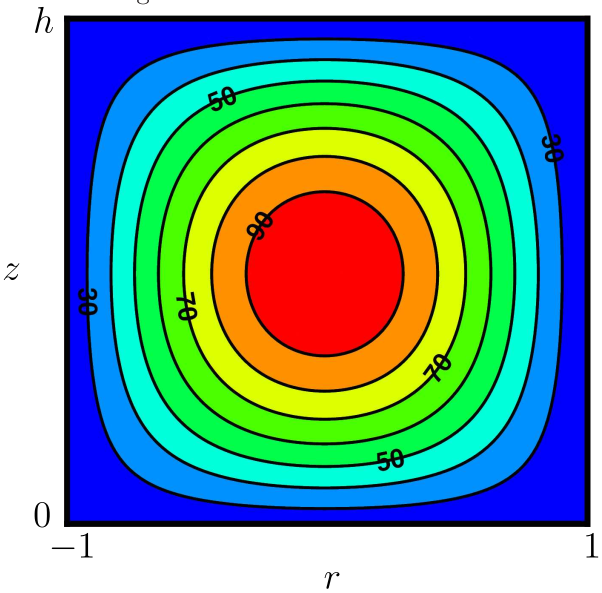

FIG. 15. (Color online) Temperature profile obtained from solution (31) at $t = 0$.

Average temperature

We can obtain the average temperature in the container at any time by integrating in the following way:

$$T_{av}(t) = \frac{\int_0^h \int_0^{2\pi} \int_0^1 T(r,z,t)\, r dr\, d\theta\, dz}{\int_0^h \int_0^{2\pi} \int_0^1 r dr\, d\theta\, dz}$$
$$= \frac{2}{h}\int_0^h \int_0^1 T(r,z,t)\, r dr\, dz. \tag{32}$$

Replacing T by its expression from solution (31) and integrating over z, we obtain:

$$T_{av}(t) = \frac{4\, T_0}{\pi}\, \exp\left[-\left(\frac{\pi^2}{h^2} + b^2\right)\kappa\, t\right] \int_0^1 J_0(b\, r)\, r dr. \tag{33}$$

Using the definition of b and J_0, we can numerically evaluate the above expression:

$$T_{av}(t) \approx 0.275\, T_0\, \exp\left[-\left(\frac{\pi^2}{h^2} + b^2\right)\kappa\, t\right]. \tag{34}$$

The average temperature during the cooling is a decreasing function of time, hence, it is maximum at $t = 0$: $T_{av} \approx 0.275\, T_0$, which, in dimensional quantities becomes: $T^*_{av} \approx T_{av}\, \tilde{T} + T^*_{atm}$. It follows that $T^*_{av} \approx 42°$C. This temperature is already below the desired temperature range [75°C;85°C] and is not physically sound. We thus conclude that this calculation is faulty and is of no help to the brewing of tea without further improvement.

[1] M. Moore, “The rise and rise of mandarin – but how many will end up speaking it?” Telegraph (2011).
[2] That says it all about the quality of British tea.
[3] Note that none of them is from any of the Guineas.
[4] Australian and Polish.
[5] Originally French, his identity has drifted west with time.
[6] As he wants to be called.
[7] R. Arthur, “The instant expert: expensive taste,” The National (2011).
[8] B. Ponedel, “Computer names,” Email exchange with C. Beaume (2015).
[9] The original measure, 7 to 9 cups, did not make SI sense.
[10] The authors doubt about the value of this statement in the United Kingdom.
[11] The authors have not yet managed to unravel the meaning behing this mysterious statement made by BP.
[12] Again, the original instructions did not make SI sense.
[13] How often does he not pay attention is out of the scope of the present paper.
[14] R. Twinings, “A new indicator for tea brewing,” Proc. R. Soc. Tea **1092**, 72–79 (1983).
[15] B. Ponedel, “Tea tips,” Journal of Tea and Stuff **2**, 174–196 (2012).
[16] A. Tetley, “How to cold brew successfully,” Proc. R. Soc. Tea **1096**, 36–48 (1984).
[17] A. Tetley and R. Twinings, “Hot or cold brewing, that is the question,” Annu. Rev. Tea **6**, 27–65 (1986).
[18] N. Lipton, “This is my cup of tea,” Annu. Rev. Tea **37**, 1–42 (2007).
[19] The authors are not responsible for the grammatical mistake, the jar’s inscription is reported as is.
[20] H. Wallop, “Surströmming: tasting the smelliest food in the world,” Telegraph (2014).