Calculating the optimum temperature for serving hot beverages

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\section*{ABSTRACT}

Hot beverages such as tea, hot chocolate, and coffee are frequently served at temperatures between 160 °F (71.1 °C) and 185 °F (85 °C). Brief exposures to liquids in this temperature range can cause significant scald burns. However, hot beverages must be served at a temperature that is high enough to provide a satisfactory sensation to the consumer. This paper presents an analysis to quantify hot beverage temperatures that balance limiting the potential scald burn hazard and maintaining an acceptable perception of adequate product warmth. A figure of merit that can be optimized is defined that quantifies and combines both the above effects as a function of the beverage temperature.

An established mathematical model for simulating burns as a function of applied surface temperature and time of exposure is used to quantify the extent of thermal injury. Recent data from the literature defines the consumer preferred drinking temperature of coffee. A metric accommodates the thermal effects of both scald hazard and product taste to identify an optimal recommended serving temperature.

The burn model shows the standard exponential dependence of injury level on temperature. The preferred drinking temperature of coffee is specified in the literature as 140 ± 15 °F (60 ± 8.3 °C) for a population of 300 subjects. A linear (with respect to temperature) figure of merit merged the two effects to identify an optimal drinking temperature of approximately 136 °F (57.8 °C).

The analysis points to a reduction in the presently recommended serving temperature of coffee to achieve the combined result of reducing the scald burn hazard and improving customer satisfaction.

\section*{1. Introduction}

The high temperature range typically recommended for serving hot beverages commercially (recommended to be on the order of 185 °F (85 °C)) presents a substantial scald burn hazard to consumers \cite{1}, and many such injuries occur annually \cite{2,3}. A reduction in the number and severity of these injuries has been a long-standing objective within the burn prevention community. One step toward that goal is to construct an analysis tool that can be used to predict the quantitative effect of altering the beverage temperature on changing the potential for scald injury.

The propensity for hot liquids to produce burn injuries to skin has been measured and modeled for more than a half
century [4,5]. These analysis tools were accepted and applied very widely within the biomedical engineering and science community. Based on experimental and computationally derived data, it is very straightforward to predict the benefit in reduced injury potential that would be gained by lowering the service temperature of hot beverages. The incremental benefit is largest at the highest temperatures owing to the exponential dependence of the rate of injury on the absolute temperature. The obvious conclusion is that the lower the serving temperature, the less is the potential for causing a burn in the case of a spill accident.

However, it is not possible to reduce the temperature of a hot beverage without limit because at some point consumers will discern that their hot beverage is not warm enough to satisfy their expectations. It should be anticipated that for a population of users a spectrum of preferred drinking temperatures would be identified, with some being hotter and some colder than the average value. If a threshold temperature range for satisfaction can be identified, then higher values would have the combined effects of increasing burn hazard and decreasing consumer satisfaction, both of which are undesirable. At sub-threshold temperatures, injury potential would continue to be reduced, as desired, but consumer satisfaction would be compromised. Identifying the incremental contributions of a change in beverage temperature (as a function of the absolute value of temperature) to altering the scald hazard and the product quality is one of the primary challenges addressed in this study.

Coffee is an extremely popular beverage. Nearly 8 of 10 Americans drink coffee, consuming more than 300 million cups per day, many of which are served commercially. The National Coffee Association of U.S.A., Inc., recommends that the temperature of a coffee must be maintained between 180 °F and 185 °F (82.2 °C and 85 °C) for optimal taste [6,7]. This recommendation has carried considerable influence in establishing the policies for serving temperatures for many commercial vendors.

In contrast to this recommended serving temperature, data has been published recently that identifies an average of approximately 140 °F (60 °C) as the temperature at which consumers prefer to drink coffee [8]. A group of 300 subjects were enabled to adjust their coffee temperature by adding condiments and dilution with cooler beverage to achieve drinking conditions they considered most favorable. For this study group the standard deviation in drinking temperature was about ±15 °F (8.3 °C). The preferred drinking temperature is considerably lower than is traditionally recommended for serving coffee, and such a reduction would have a major impact on lowering the number and severity of scald burns caused by hot beverage spills.

The challenge addressed in this study is to identify an algorithm for combining the quantitative thermal effects of reducing scald burn hazard while maintaining consumer perceived product quality. Quantitative measures of how temperature influences both of these phenomena are developed individually and then combined into a single metric for optimization of serving temperature.

The hypothesis of this study is that a tradeoff can be defined in specifying hot beverage serving temperatures whereby a compromise is achieved in reducing scald burn hazard while maintaining acceptable product quality.

2. Scald burn model

This paper addresses the issue of how the current serving standards for coffee could be adjusted based on consumer taste preference to provide a level of protection to individuals from scald burns. The analysis approach adopted is to simulate the injury process using an Arrhenius-kinetics based mathematical model for molecular damage, as postulated more than a half century ago by Henriques and Moritz [4,5] and Büttnér [9,10], to describe and predict thermal insult effects in skin. The kinetics approach to modeling burn injury has been adopted by a large number of researchers over the intervening years, and its veracity has been well documented. The methods and results of prior work on modeling thermal injury have been reviewed periodically in the biomedical engineering literature [11–14] and are well accepted. The current study applies this well-accepted approach to modeling thermal injury in combination with recent data on the customer preferred temperatures for drinking hot coffee to develop a new quantitative metric for defining a serving temperature that accommodates considerations of both scald safety and customer perceived product quality.

The modeling process is implemented in two steps. First, the transient expression of the temperature field within the affected tissue is calculated as a function of the system constitutive properties and geometry, plus the thermal conditions imposed on the surface. Next, the temperature data is applied in an injury kinetics algorithm to calculate the extent of accrued damage.

The phenomenological model applied in the present study is based on the analysis of human skin as a system, which requires identifying the pertinent features and properties. In many scald burns the lateral extent of the burned area is measured on a length scale of centimeters, whereas the depth of the thermally affected tissues is more than an order of magnitude thinner. This small depth/breadth aspect ratio justifies the assumption that from a local perspective spatial gradients in the temperature field are greatest normal to the skin surface. Further, the thickness of the skin is very small in comparison with the radius of curvature of the skin surface over nearly all sites on the body. These aggregate assumptions lead to the addressing of the heat transfer and burn processes as varying along a single Cartesian coordinate into the skin, which reduces to the problem of one dimensional transient phenomena in a semi-infinite medium, as illustrated in Fig. 1.

When a hot beverage is spilled onto the surface of the skin heat is transferred via convection to the tissue, from which it diffuses inwardly. The convective process consists of a combination of diffusion along a temperature gradient and advection due to bulk motion of the liquid. The diffusive component of convection will always be present, but the role of advection may vary widely depending on factors such as the amount of liquid spilled the type of clothing covering the affected area of skin. The thickness of the body is such that the diffusing heat will penetrate continually deeper without encountering another exterior surface. This arrangement is known as a semi-infinite medium, and the boundary conditions and properties are described collectively in terms of the information given in Fig. 1.
Skin is a composite structure that consists of a very thin overlying epidermis and a much thicker underlying dermis and subcutaneous fat. Each layer has unique thermal properties. The dermis has a rich microvascular network that provides for convective heat transfer between perfused blood and the tissue in which it is embedded, but at the elevated temperatures associated with a burn the perfusion is terminated rapidly and has no local thermal effect. Thus, heat transfer internal to the skin in the core region of a burn can be assumed to be exclusively via conduction.

Although the epidermis presents a key environmental barrier and has a critical physiologic role in determining the depth and characteristic of a burn, from a heat transport perspective its thermal diffusion properties are only slightly distinguished from those of the dermis, and its relative thickness is quite small. Therefore, the differential thermal properties that it may have in comparison with the dermis will be neglected. Further, the effective duration of the scald insult owing to spilling a cup of hot beverage is likely to be measured in no more than about 4 s. Once the liquid is spilled from the cup it will lose heat to the environment via conduction to the skin, convection to the air, and evaporative cooling.

If the liquid is spilled onto an area covered by clothing, it will be absorbed and retained at the site of the insult as a function of the material, prolonging the insult by retaining the liquid at the site. Differing clothing ensembles can have quite distinctive thermal effects, and it is impossible to develop a general representation to simulate this influence. The lead author has conducted informal, unpublished tests with one or two layers of denim and/or cotton typical of apparel worn indoors and observed an effective drop of approximately 10% of the differential between the liquid and the initial surface temperature, which can translate to roughly 5 °C (9° F). There is no noticeable delay in the thermal response at the underlying surface on the time scale of the insult process, given the typical absorbency of the above materials. Thus, rather than complicating a simulation model by adding an overlying composite structure, a more simple, but still rational, approach is to reduce the temperature of an insulating beverage on the skin surface.

The mathematical representation of the heat diffusion process in skin in accord with the foregoing assumptions follows. The temperature within the skin, \( T(x,t) \), is a function of position, \( x \), and time, \( t \), according the thermal diffusion equation.

\[
\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}
\]

where \( \alpha \) is the thermal diffusivity. Note that no terms are introduced to account for the effects of internal convection associated with blood perfusion or of metabolic heat generation. Modification of the thermal diffusion equation to include these effects results in the well-known Pennes equation \([15,16]\). These two effects are omitted from the present analysis since it is well documented in experimental studies of thermal stress in a tissue preparation in which microvascular perfusion can be observed continuously that there is a nearly immediate cessation of local blood flow when the temperature is raised to a level consistent with causing burns \([17]\). Further, the rate of metabolic heat generation is very small compared to the rate of heat diffusion during the acute burn process.

The thermal properties of skin are taken from a recent compendium \([18]\). Boundary conditions are defined at the skin surface and deep in the tissue beyond the zone of influence of the thermal insult. In the limiting case of highly effective convection with a liquid fluid, the surface condition will approach that of an applied temperature. Since this solution will result in a worst case burn for a defined insult potential, it is adopted for this analysis and specified as \( T(x,0) = T_i \). The far field and initial uniform temperatures in the skin are both equal, \( T_i \). The analytical solution for this problem is expressed as the error function \([19]\).

\[
\frac{T(x,t) - T_i}{T_s - T_i} = \text{erf}\left(\frac{x}{2\sqrt{\alpha t}}\right)
\]  

The mathematical description of the temperature given in Eq. (2) is applied to calculate the local rate of thermal damage, which then is integrated over the total time of the insult to yield a net level of injury. The damage rate is assumed to occur as a protein denaturation, which can be described in terms of an Arrhenius process kinetics model. The quantitative rate of
accumulation of injury is calculated in terms of a function denoted by $\Omega$.

$$\frac{d\Omega(x,t)}{dt} = Ae^{-\left(\frac{\Delta E}{RT(x,t)}\right)}$$ (3)

where $\Omega$ is numerically related to the severity of injury by a nonlinear scale shown in Table 1. The total injury after a time $t$ of thermal insult is obtained by integrating Eq. (3) over that period.

$$\Omega(x,t) = \int_0^t \frac{d\Omega(x,t)}{dt} dt = \int_0^t Ae^{-\left(\frac{\Delta E}{RT(x,t)}\right)} dt$$ (4)

The values for the scaling factor, $A$, and the activation energy, $\Delta E$, are derived from experimental data for thermal damage processes executed over the range of temperatures of interest. These types of experiments and analysis have been conducted by numerous investigators since the initial work of Henriques and Moritz [4,5]. Although many alternative sets of coefficients exist and have been compared [20,21], the most frequently applied set is that of Henriques and Moritz, as given in Table 1. Both Eqs. (2) and (4) are easily solved via a simple Excel spreadsheet for the range of states and properties of interest [22,23], which was applied for the present study.

An example of the solution for Eq. (2) is shown in Fig. 2 for a sudden increase in surface temperature from 34 °C to 87.8 °C (93.2–190 °F). Transient temperature profiles are shown for three depths in the skin, 80 μm, 0.5 mm and 1.0 mm. These depths represent the nominal interface between the epidermis and dermis, and shallow and mid level positions in the dermis. The heat applied at the surface diffuses over time into the skin so that with greater depths there is an increasing delay in response and a diminution in the magnitude. As is readily observed from Eq. (2), the total magnitude of the thermal response scales linearly with the level of temperature increase at the surface.

The transient temperature histories in Fig. 2 were substituted into Eq. (4) to calculate the resulting development of thermal injury at the three depths, as plotted in Fig. 3. The differential among the three curves is much greater for injury than for temperature owing to the exponential nature of the injury function. The rate of injury accelerates increasingly as the temperature is raised so that the highest temperatures play the most significant role in the process. This data demonstrates clearly the nonlinearity of the injury function, but it is even more explicit in Fig. 4 in which injury is plotted for a common depth for a series of simulated burns ranging from 100 °F to 190 °F (87.7 °C). In Fig. 4(a) where injury is plotted on a linear scale, the outcome is totally dominated by temperatures from 175 °F (79.4 °C) and upward. Compared with the injury produced at these highest temperatures, the results at lower temperatures are very small. Since the injury function is exponential, it is more instructive to view it on a logarithmic scale, as shown in Fig. 4(b). As expected, the log of injury is a straight line function of temperature. This linear relationship is very useful for developing the targeted metric for the present study.

### Table 1 – Constitutive properties in the thermal damage model (Eq. (4)), as adopted from refs. [5] and [14]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Scaling factor</td>
<td>$3.10 \times 10^{38}$</td>
<td>1/s</td>
</tr>
<tr>
<td>$\Delta E$</td>
<td>Activation energy for burn process</td>
<td>$6.27 \times 10^{8}$</td>
<td>J/kmol</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Duration of burn</td>
<td>4</td>
<td>s</td>
</tr>
<tr>
<td>$R$</td>
<td>Universal gas constant</td>
<td>$8.314 \times 10^2$</td>
<td>J/kmol K</td>
</tr>
<tr>
<td>$D$</td>
<td>Damage function</td>
<td></td>
<td></td>
</tr>
<tr>
<td>First degree</td>
<td></td>
<td>0.53</td>
<td>–</td>
</tr>
<tr>
<td>Second degree</td>
<td></td>
<td>1.0</td>
<td>–</td>
</tr>
<tr>
<td>Third degree</td>
<td></td>
<td>10$^4$</td>
<td>–</td>
</tr>
</tbody>
</table>

### Fig. 2 – Temperature rise at three depths within the skin in response to a step increase in surface temperature from 34 °C to 87.8 °C (93.2–190 °F).

### Fig. 3 – Calculated injury for the thermal insult conditions shown in Fig. 2.

### 3. Preferred coffee drinking temperature data

Lee and O’Mahony [8] recently published data from a study to determine consumer preferences for the drinking temperature of coffee. Large cohorts adjusted the temperature of their coffee by mixing from hotter (85.0–90.6 °C) (185–195.1 °F) and cooler (21.1–23.8 °C) (70–74.8 °F) sources. Two separate experiments were conducted. One cohort ($n = 300$) also had the opportunity to add condiments, which contributed to adjusting the temperature, whereas the second ($n = 108$) all drank...
black coffee. The summary measurement data is presented in Table 2. In all experiments the mean chosen drinking temperature for coffee was close to 60 °C (140 °F). This value is substantially lower than the industry recommended standards and would result in a substantial reduction in the incidence and severity of scald injury in the event of a spill onto human skin.

Given the statistical nature of this data, it should be possible to represent the probability that a given fraction of the population would prefer to drink their coffee at a given temperature. For this purpose it was assumed that the preferred drinking temperatures followed a normal distribution, normalized about the mean, as shown in Fig. 5. The distribution density function, \( d \), is defined in Eq. (5).

\[
d(T, \bar{T}, \sigma) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{(T-\bar{T})^2}{2\sigma^2}}
\]

for which \( \bar{T} \) is the arithmetic mean of the temperatures chosen by the test subjects and \( \sigma \) is the standard deviation of the data.

As temperature deviates progressively either higher or lower from the mean value, the fraction of consumers who are satisfied with their coffee becomes smaller. The maximum probability of any single temperature being selected occurs at the mean value (about 2.7%), and diminishes asymptotically to zero for both higher and lower temperatures, as calculated by Eq. (5). Thus, this distribution function affords the ability to quantify the effect of altering temperature on perceived coffee product quality, which can be combined with the thermal effect on scalding potential to obtain an overall metric combining these two phenomena.

### 4. Combined temperature metric

A major challenge of this study is to develop an algorithm that provides a rational basis for comparing the influence of beverage temperature on causation of scald burns and on consumer product satisfaction. For purposes of this analysis, consumer product satisfaction as reflected in preferred drinking temperature of hot coffee is referred to as quality. Since the burn is a negative event, it is logical to view coffee temperature in terms of a metric that reflects consumer dissatisfaction (also negative), rather than satisfaction (positive), with product quality. Further, if the scald and quality metrics can be scaled properly, they can be combined to define

<table>
<thead>
<tr>
<th>Number of subjects</th>
<th>Coffee combination</th>
<th>Mean temperature °C (°F)</th>
<th>Standard deviation °C (°F)</th>
<th>Range °C (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>108</td>
<td>Black coffee—strong</td>
<td>59.3 (138.7 °F)</td>
<td>6.5 (11.7 °F)</td>
<td>41.0–72.4 °C (98.1–190.4 °F)</td>
</tr>
<tr>
<td></td>
<td>Black coffee—weak</td>
<td>60.4 (140.7 °F)</td>
<td>6.7 (12.1 °F)</td>
<td>41.9–78.5 °C (107.4–178.3 °F)</td>
</tr>
<tr>
<td>300</td>
<td>Coffee with/without condiments</td>
<td>59.8 (139.6 °F)</td>
<td>8.1 (14.8 °F)</td>
<td>36.7–88.0 °C (98.1–190.4 °F)</td>
</tr>
</tbody>
</table>

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Fig. 4 – Level of injury after 4 s at a depth of 0.1875 mm for step changes in surface temperature ranging from 100 °F to 190 °F (37.8–87.8 °C) for 4 s. (a) Linear scale for injury. (b) Logarithmic scale for injury.
a measure that reflects the overall influence of changes in hot beverage serving temperature. This measure can be minimized so as to determine an optimal hot beverage temperature that accounts fairly for both consumer desire for quality and reduction of scald burn hazard when the beverage is spilled onto human tissue. For present purposes, this measure has been named the “figure of demerit” (FoD) since it reflects reduced performance for both injury avoidance and consumer satisfaction, and it is the simple sum of metrics for the temperature effects on scald hazard and product quality.

According to Eq. (4), scald injury severity varies exponentially with temperature. In contrast, customer satisfaction with drinking temperature varies with temperature according to a normal distribution. Thus, these effects cannot be combined directly without having one dominate the other. However, if the logarithm of the scald injury function (\(I(t)\)) is applied, as illustrated in Fig. 4(b), then the scald and quality metrics can be summed to calculate the FoD that includes an approximately equivalent influence of each factor. This operation is shown in Eq. (6).

\[
\text{FoD}(T) = \frac{\log(I(T))}{2} + 3.5\left(1 - \frac{d(T)}{d(T)}\right) + 0.70
\]  

(6)

As is seen in Fig. 4(b), the range on the first term relating to scald injury potential is about \(-3.5\) to \(2.6\). The second term can take values from 0 to 3.5. The added constant ensures that the value of FoD is always positive. The solution of Eq. (6) for temperatures over the range 100 °F to 190 °F (37.8–87.8 °C) is plotted in Fig. 6.

5. Discussion

By applying the FoD criterion, an optimal drinking temperature of approximately 136 °F (57.8 °C) is defined. However, since the FoD as a function of temperature passes through a minimum value in this region, the slope of the curve is zero or at values close to it. Thus, it is not appropriate to specify a distinct value for the optimal temperature. Rather, a range of temperatures can be identified for which the FoD is close to its minimum value. This range extends from approximately 130 °F to 140 °F (54.4–60 °C), where the FoD values are 0.13 and 0.15, respectively. Specification of an optimal range of serving temperatures allows for uncertainties in the model for measured tissue properties and assumptions to match actual physiological processes.

The FoD demonstrates a highly asymmetric behavior with respect to temperature, which is understood as it is a combination of two primary components. The data for consumer preferences for drinking temperature of hot coffee is assumed to be completely symmetric with a normal distribution about the mean value, with no indication of a bias toward either higher or lower values. The data by Lee and O’Mahony [8] provide on indication that such a bias exists. Conversely, the injury function is exceptionally asymmetric with temperature, rising exponentially with continuously increasing temperatures. As a consequence, the FoD has a strong bias toward recommending lower temperatures for hot beverages. The effect of the scald hazard is far more important at temperatures above the average consumer preferred drinking temperature than it is below. Clearly, the combination of these two diverse considerations provides a rational basis for making a recommendation for hot beverage temperature.

It must be pointed out that the drinking temperature is often times different, and lower, than the serving temperature. This difference can depend on a number of factors such as the time delay between service and consumption, the thermal properties of the container into which the beverage is decanted, and the quantity and temperature of condiments added. Scald accidents occur most frequently in conjunction with the beverage being served, when it is hottest, and the consumer drinks the beverage when it is coolest. This analysis assumed that there was a single temperature of the beverage that could be used for the analysis, when in practice there may be a range of temperatures to be considered. The analysis could be modified to include these other factors, but they would require making further assumptions that are specific to particular cases of application. The most conservative and safe approach is to use a single temperature for the analysis unless there is compelling evidence to motivate otherwise.

Another factor which is not included in the analysis is the effect of clothing overlaying the site of a hot beverage spill. It is well known that the clothing will provide a thermal buffer against transfer of heat from the liquid to skin. A rough estimate of the temperature diminution by clothing is 5 °C (9 °F), but this number can vary widely. On the other hand,
depending on the absorbency of the materials, it will prolong the period of contact between the liquid and skin, exacerbat-
ing the scald process. It is impossible to incorporate any general consideration for clothing effects into the analysis. In one extreme, there are instances in which a hot beverage is spilled directly onto bare skin. The opposite extreme is when clothing provides complete thermal protection against a spill. The most conservative and safe approach to treating the effect of clothing is to omit this influence from the analysis, as is done in the present work.

6. Conclusions

This study has demonstrated that it is possible to define an algorithm whereby one can combine balanced considerations of realistically minimizing scald hazard from a spilled hot beverage with maintaining a standard of product quality acceptable to consumers so as to establish an optimal serving temperature (or range of temperatures) for hot coffee. The underlying considerations for both scalding and product quality are based on objective, documented scientific data. Application of this data to derive a specific algorithm requires invoking a set of assumptions cogent with particular user environment and priorities. As the environment and priorities are altered, then it is expected that the recommendation derived from the algorithm would change accordingly. However, the authors believe that the present embodiment of this analysis will serve as a general guideline that will be appropriate to a broad spectrum of settings in which hot beverages are served. Adjustments in the algorithm to account for other needs as they may be defined can be accomplished quite easily.

Conflict of interest statement

Neither author has any financial or personal relationships with other people or organizations that could inappropriately influence or bias their work on this manuscript.

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