Engineering an Optimal Cocoa Preparation Protocol (OCPP)
Task 3 for Science, Technology, and Society
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The Problem and its Significance

One of the wedding gifts that my wife and I received was a large supply of cocoa powder in a nice lidded container (Figure 1). Since the powder had been separated from its original packaging (and thus its instructions), its use was not completely obvious. Pilot testing, in which the powder was mixed with cold milk and then microwaved, resulted in "boil-over" of the milk. Therefore, for the purposes of this paper, the problem was considered to be the need for an Optimal Cocoa Preparation Protocol (OCPP) that avoids boil-over. An ideal solution will be defined as one that not only prevents boil-over, but does so with as few changes to the existing protocol as possible (e.g., using the same ingredients as before).

Figure 1: The reagent characterized in this study (cocoa powder from an unknown source).

While this cocoa preparation problem is admittedly a minor one, it is reminiscent of more substantial engineering challenges. Engineers often seek to counteract or control natural forces in order to minimize spills, breaks, and other disasters and inconveniences. Here, the effects of increasing temperatures on dissolved gases (see below) lead to inconveniences such as a messy microwave to clean and/or burns from a hot, dispersed liquid. In this way, the cocoa study is in the spirit of Science Buddies (Hess et al., 2011), whose web page on engineering projects encourages students to include small and silly items in their "bug lists."

Background

The problem is depicted visually in Figure 2. The cocoa powder does not dissolve completely in cold milk even when stirred vigorously. When the mixture is then heated in the microwave, it erupts over the sides of the container.

Figure 2: The cocoa powder does not fully dissolve in cold milk; some clumps float on top (left). When the mixture is heated in the microwave, it spills (right).

Why do fluids erupt like this? Schiffmann (1989) attributes boil-over to the expansion and coalescence of gas bubbles trapped in a liquid. If the liquid is highly viscous and/or is heated unevenly, the trapped bubbles get larger and become more likely to cause a boil-over when they do eventually reach the surface.

Schiffmann's analysis may apply to the current cocoa problem in two respects. First, milk is at least 60% more viscous than water (for skim milk; Bateman & Sharp, 1928), so it may boil over more readily than water. Second, the stirring of cocoa powder into cold milk creates a lumpy mixture that is presumably even more viscous and even more liable to boil over.

The mixture is lumpy because the cocoa powder remains largely undissolved in the cold milk. Why is the solubility so poor? The question is not easy to answer, as cocoa powder is composed of numerous substances (Tomas-Barberán et al., 2007; Andres-Lacueva et al., 2008). However, as a general rule, temperature does affect solubility. Therefore, solutions to the cocoa problem might entail finding a milk temperature that is optimal for dissolving cocoa powder.

Methods and Results

A comparison was made of six different glasses: (A) 1% milk, cocoa powder added before heating; (B) water, cocoa powder added before heating; (C) skim milk, cocoa powder added before heating; (D) whole milk, cocoa powder added before heating; (E) 1% milk, chocolate chips added before heating; (F) 1% milk, cocoa powder added after heating. Glass A represents the original, spill-prone protocol; the other glasses represent alternative protocols, and thus possible solutions to the problem posed above. That is, boil-over could potentially be prevented by using water instead of milk (B), by using skim milk instead of 1% milk (C), etc.

Although I prefer large mugs of cocoa, "micro-scale" experiments were conducted with smaller volumes to reduce the consumption of milk and cocoa powder. Identical glasses, each holding up to 11 fluid ounces, were filled with 6 fluid ounces of milk or water and one tablespoon of cocoa powder or Nestle chocolate chips. A 950-Watt microwave on hand (Kenmore model 665.68601991) heated each sample for 80 seconds at 100% power. Table 1 summarizes the conditions and results of these experiments.

Table 1: Variations in the cocoa preparation protocol

	Liquid	**Additive?**	**Solubility of additive when added**	**Boil-over?**
(A)	1% milk	Cocoa powder, before heating	Low	Yes
(B)	Water	Cocoa powder, before heating	Very low	No
(C)	Skim milk	Cocoa powder, before heating	Very low	Yes
(D)	Whole milk	Cocoa powder, before heating	Low to moderate	Yes
(E)	1% milk	Chocolate chips, before heating	No	No
(F)	1% milk	Cocoa powder, after heating	High	No

Solution to the Problem

According to the criteria and constraints introduced earlier, and the results presented in Table 1, protocol F is the best solution to the problem because it (i) avoids spill-over and (ii) uses the same ingredients (i.e., 1% milk and cocoa powder) as the original protocol. The other protocols were not ideal in that they led to boil-over (A, C, D) and/or deviated from the original set of ingredients (A, C, D, E). To verify the suitability of protocol F, it was used to prepare an additional glass on a different day; results were the same as before (high solubility, no boil-over).

Protocol F is an excellent solution to the very specific problem defined here; however, its utility is limited in two important ways. First, an OCPP should preferably produce cocoa that not only stays in its container but tastes delicious; however, taste-testing of the samples was forbidden by institutional authorities on the grounds that it would constitute "experimentation on vertebrate animals." Thus, the question of whether protocol F's cocoa actually tastes good remains unresolved. Second, the solution presented here does not necessarily apply to variations on the original problem. For example, we do not know whether other brands of cocoa powder behave similarly to the mystery brand tested here. I did not test drinking receptacles that hold different volumes, although receptacle size would influence the likelihood of boil-over of a given amount of liquid. Likewise, I did not vary microwave time, even though different people prefer cocoa heated to different temperatures. (However, I did not strictly control temperature either; different glasses may have reached somewhat different temperatures, since their contents may have had somewhat different specific heat capacities.)

The above limitations aside, these findings may be applicable to other drinks prepared by dissolving a powder in a liquid – for example, instant coffee made from coffee crystals and water. If the drink is to be served hot, my data suggest that the powder should be added after heating the liquid, rather than beforehand. However, this approach would need to be validated empirically for any given combination of powder and liquid.

Further Discussion: Factors Affecting Boil-Over

As expected, the "default" protocol (A: add cocoa powder to cold 1% milk, then heat) led to boil-over. However, boil-over could be prevented by using water instead of milk (glass B), by using chocolate chips instead of cocoa powder (glass E), or by heating the milk in the absence of cocoa powder (glass F). Thus, boil-over appears to be influenced by multiple factors.

The presence of an undissolved additive in milk was not itself sufficient to cause boil-over, as demonstrated by the undissolved chocolate chips in glass E. The difference between glasses A and E may be that the clumped powder on the top of A hindered gas bubbles' escape from the milk, causing an accumulation of larger bubbles and an eventual boil-over, whereas the undissolved chocolate chips stayed at the bottom of glass E, where they presumably did not hinder the gas bubbles' escape.

Why did glass A boil over while glass B did not, even though cocoa powder accumulated at the top of both liquids? Perhaps more viscous liquids, such as milk, trap larger gas bubbles and thus are more susceptible to boil-over, as suggested above. However, the different types of milk – 1% (A), skim (C), and whole (D) – all boiled over despite having different levels of fat and thus different viscosities (Fernandez-Martin, 1972). The whole-milk glass (D) actually came the closest to not spilling, only erupting in the last two seconds of the 80-second heating period. Perhaps the extra milk fat contained in whole milk exerts multiple self-canceling effects on boil-over tendency. On the one hand, whole milk is more viscous than other milk (Fernandez-Martin, 1972), again increasing boil-over risk (see above). On the other hand, the whole milk appeared to dissolve the cocoa powder somewhat better than the low-fat or skim milk did (consistent with the inclusion of hydrophobic compounds like polyphenols in cocoa powder; Tomas-Barberán et al., 2007), resulting in fewer, smaller clumps atop the milk and perhaps less trapping of bubbles and a lower boil-over risk.

Reflections on the Engineering Process

This study resembled a scientific study in that data were gathered to answer a question. However, it was an engineering study in the sense that the main goal was to solve a practical problem, not to test a scientific hypothesis. While the study was clearly related to scientific concepts – in particular, the physical chemistry of solutions and solubility – the measurements were not designed to shed light on the underlying physical and chemical forces; rather, they assessed whether the engineering problem had been solved (i.e., "Does this protocol prevent boil-over?").

Engineering studies are generally iterative, with multiple rounds needed to refine testing and reach a fully vetted solution. While the iterative nature of this study was not emphasized above, the volumes and microwave settings used were settled via trial and error. In addition, the first set of glasses had to be abandoned due to incompatibility with the microwave. Glasses C and D were not included in the initial testing, but were added later to clarify the possible influence of milk viscosity on boil-over. These additions to the full dataset (Table 1) showed that changing the type of milk (glasses A, C, and D) was not itself a solution to the problem, and that the best solution was to add the cocoa powder after heating the milk (glass F). Finally, as a final step in choosing among the possible solutions, protocol F was repeated to confirm its suitability.

References

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