The Perfect Pour: Beer Foam Physics and the Art of Dispensing Beer

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Though it may seem trivial and unimportant, the complexities of the college males alcoholic beverage of choice, deserve further inspection. The physics associated with dispensing and consuming beer provide sources of interest throughout the community. The production of the beer itself is related more directly to the chemistry and microbiology of the concoction, and as such will not be covered in this paper. Beyond the brewing process however, there is a great deal of physics involved. Concerning ourselves solely with the bubbles contained in the beer we will see that viscosity, gas content, relative density and the surface tension are four parameters which show major importance. The theory and equations governing head formation, sustainability and decay are presented and discussed.

I. INTRODUCTION

A. Ancient Times

As early as 6,000 years ago, the Sumerian empire was brewing a fermented grain beverage which resembled an "inebriating pulp." Historical reference to this beverage is the earliest relative of the beer we know today. This drink was considered divine and as such, offered to the gods.

Throughout the Babylonian empire beer was a highly appreciated drink and brewing, a lauded skill. So much so that a beer ration was established for all people, dependent upon their social rank. "A normal worker received 2 liters, civil servants 3 liters, and administrators and high priests 5 liters per day." This sentiment was echoed in Egypt where the act of brewing was so important, that a hieroglyph was created for "brewer"[1]

Through Greek and Roman times, beer continued to be brewed, and continued to be popular. However, as time passed and grape growing began to take hold, the divinity was stripped of the drink. Wine was considered the drink of the gods, and beer brewing only took place in the outskirts of the Roman empire, where wine was hard to obtain. In fact, an early historian of the Roman Antiquity, Tacitus, illustrates this in his text, *The Germania* on the Teutonic tribes of northern Europe where he writes, "To drink, the Teutons have a horrible brew fermented from barley or wheat, a brew which has only a very far removed similarity to wine."[2] The Teutonic tribes revered for the drink, and continued to considered it divine. This divinity stemmed from the mood-altering properties of the drink and it was considered, that the beer contained a spirit of a god, as it so possesses the spirit of the drinker.[1]

B. The Middle Ages

Originally, flavouring came from a mixture of herbs and spices, called grut. This grut was able to be licensed, a form of early patent, where a recipe for flavour could be protected for exclusive use by a brewer. Lacking today's knowledge of the mechanics of brewing, the grut recipes often spoiled, but for reasons unknown and was often blamed on supernatural beings.

Brewers found that adding hops, the flowers of the hop plant, served as a great way to add bitterness to their beer. A side benefit was that they increased the stability of the beer and added predictability to the brewing process. Upon their introduction, the exclusive brewing right associated with grut recipes was nearly vanquished, and as such, hops were initially banned from usage. This did not stop the brewers. As time passed and in spite of illegality, growing number of breweries utilized hops to brew their beer, simply due to the increased predictability afforded by hop usage. Fewer batches spoiled and the product began to resemble that which we know today.

Over the next 300 years, very little changed, so called brewing centers or "beer capitals" developed (at one point Hamburg, Germany contained over 600 breweries). Increased knowledge about the brewing process, and more specifically the temperatures at which certain beers can be brewed, further reduced the number of spoiled batches.[2] That said, the technology available at the time was of little use, and the ability to exploit this information would not be available until the Industrial Revolution.

C. The Industrial Revolution

The advent of the Industrial Revolution added scientific techniques to aid in the art of brewing. By the mid-19th Century it was already well known, and scientifically proven, that brewing good beer required certain temperatures. For example, the most popular Lager-type beer requires storage temperatures between 4°C and 10°C in order for proper natural carbonation to form. This prevented lager beers from being brewed in the summer months, as ambient temperatures were too high. Even with widespread usage of block ice and deep, cold cellars, these temperatures could not be reached, or adequately regulated.[2]

That was until Carl von Linde (also known for his achievements in liquifying air) changed the industry; inventing the first reliable and efficient compressed-ammonia refrigerator. Von Linde's invention allowed for comparatively precise temperature control that allowed these beers to be brewed. That

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said, it is not surprising, that his first refrigeration system was tested at a Munich brewery.[3] In the last 150 years even less has changed, however, modern research continues to explore this divine beverage.

II. FURTHER EXPLORATION

A. Opening

The physics of beer start to come into play in the dispensing and presentation of the beer. As these two actions are regulated by the properties of the liquid, determined by the chemistry. The most noticeable property, is the degree of carbonation.

Technically, carbonation implies that the bubble inducing gas is carbon dioxide. However, this term is generally associated with the bubbles within any beverage. Unfortunately this is not always the case. Gasification may be more appropriate, as some liquids use nitrogen for the same purpose. We will use carbon dioxide as the standard for the rest of our discussion unless other wise noted.

Everyone is familiar with the sound associated with the opening of a bottle. This is due to the equalization of pressures between the inside and outside of the bottle[4]. Prior to the opening of the bottle, the partial pressures of carbon dioxide in the liquid and air in the bottle are the same; however, once the seal is cracked, a pressure differential inside and outside the bottle is created. The relationship between the gaseous and aqueous CO_2 concentrations is now much different and the partial pressure within the liquid is much higher than that in the air. The effect of this is an equalization of the partial pressures of the aqueous and gaseous CO_2. In order for this to occur, the CO_2 must come out of solution, and the familiar rush of bubbles ensues.

However, for this rush of bubbles to be initiated, the bubbles must have a place to form. Any sort of debris, or fissure on the surface of the glass will act as a *nucleation site*, or a location where bubbles will begin to grow. This is further continued when the beer is transferred to an alternate containment vessel. Most people call this a glass.

III. THE POUR

A perfect pour is characterized by the correct amount of well constructed head. While preference varies from location to location (US and southern UK prefer little head and maximum beer, other european countries prefer their beer in the proper glass with the proper amount of head for each beer). Each pour consists of two classes of actions; those which reduce the amount of foam formation, and those that promote head formation. Depending on the type of beer, different techniques are required when pouring, the most common pouring method is illustrated in figure 1.

FIG. 1: Top: Proper 45° pouring method produces smooth, neat froth. Bottom: Incorrect pour may result in excessive, ugly, undesirable froth production[5]

1. Initially, the glass is tilted to an angle, say 45° and begin pouring. Aim the beer stream approximately 2/3 of the way up the glass.

   The reason for this tilt is to increase the surface area of the liquid in the glass, allowing CO_2 to escape quicker than it would if the beer was poured straight into the glass. As the liquid moves down the side of the glass, it will spread out and move slower. This reduces the quantity of froth as it causes less disturbance and turbulence in the beer already contained in the glass.

2. Once the beer reaches the two-thirds volume point the glass it can be slowly tilted to an upright position.

   The act of pouring straight into the glass will force air bubbles into the beer. These bubbles act again as nucleation sites, allowing more carbon dioxide to come out of solution.[4]

Now that the glass is poured, and the proper amount of head formed, we can dive into the physics of what exactly is going on.

IV. WHAT'S GOING ON?

A. Head Formation

As the bubbles do not form on their own, the characteristics of the nucleation sites (see section II A) must have an effect upon the size of the bubble.

$$R_{bubble} = [3R_{nuc}\gamma/2\rho g]^{\frac{1}{3}} \quad (1)$$

Where the radius of the bubble is given by R_{bubble}, the radius of the nucleation site is given by R_{nuc} (m); γ, the surface tension (mN$\cdot$m^{-1}); ρ is the specific gravity, (or relative density, g$\cdot$m^{-3}) of the beer; and g is acceleration due to gravity (9.8 m$\cdot$s^{-2}). Both ρ and γ do not vary significantly over a range of beers, so we will take these as constants in the analysis to follow[6].

Inputting common values[1], (R_{nuc} = 0.1 mm, $\rho \cong$ 1.010

[1] ρ typically varies between 1.000 and 1.020 while it has been measured that γ varies between 42.3 and 47

and $\gamma \cong 45$), results in bubble radii of 0.88 mm. Dropping the nucleation site radius to a tenth of this value results in bubble radii of 0.41 mm. However, it has been observed [8] that when bubbling gas into beer, bubbles of radius larger than 0.85 mm were observed, but the average radius was just 0.1 mm. To achieve this small R_{bubble}, R_{nuc} must be slightly smaller than 150 nm, and as such, the majority of nucleation sites must be exceedingly small.

B. Creaming

When you look into an already poured glass, you see bubble trains rising from points in the glass. On the walls, on the bottom and sometimes from the middle of the liquid. This is an action known as creaming, or beading, and those points of bubble formation you see are nucleation sites. The greatest contributor to this action is the gas content within the beer, as the more gas is contained within the beer, the more will attempt to release itself from solution.

$$a_n^0 = 3.11C + 0.0962\gamma - 218\rho + 216 \tag{2}$$

Where a_n^0 is the initial activity at the nucleation site, C is the carbon dioxide content (vol CO_2/vol beer, often 2.5-2.7), γ is the surface tension and ρ is the relative density of the beer.[6]

C. Stability and Foam Hardening

As the bubbles rise through the beer, they capture some of the protein molecules out of solution (those molecules with a greater affinity for CO_2 will be more likely to attach to these bubbles). These adsorbed molecules stiffen the bubble by forming a shield on it's surface. When moving through a liquid, these stiff spheres incur more friction than do bubbles with a more flexible surface, and so a more rigid bubble will travel slower. In other carbonated beverages, such as champagne, this hardening does not occur as protein concentration is 30 times lower. Additionally, triple the gas pressure within champagne increases the creaming (See section IV B), bubble growth and ascent rate, further reducing the rate of hardening.[9]

D. Head Decay

To the general observer, very little thought is put into foam decay and it is considered a simple phenomenon consisting simply, of a slow loss of foam. While this may be true, this does not remove any physics from this assumption. Research conducted in Germany, found that the rate of beer head bubble decay was governed by an equation of exponential decay. Furthermore, from what we know from above about foam stability and it's dependence on the beer contents, the rate of decay may be characteristic of the type and brand of beer (if the recipe can remain consistent). It may be additionally influenced by temperature and age (depending on the style, a second fermentation process may purposefully occur in the bottle, changing the specific gravity and surface tension of the beer as it ages). Arnd Leike was awarded the Ig Nobel prize in 2002 for this discovery (it must be added that this paper was published as a result of demonstrating the experimental method to a classroom of students). The Ig Nobel prize is awarded, by Harvard University and the Annals of Improbable Research, to those who have performed research which "first makes people laugh, then makes them think".[12] Other awards in physics have been awarded to a mathematical computation of a tea pot spout that will not drip, an a paper showing how black holes fill all technical requirements for the location of hell.[13]

This experiment was conducted by pouring a freshly opened bottle of one of three types of beer (Erdinger Weissbier, Augustinerbräu München and Budweiser Budvar), into a cylindrical beer glass. Over the period of 6 minutes, Leike recorded the height of the beer froth 15 times. Leike then applied a chi-squared test to check whether his prediction of exponential froth decay agreed with the data. How did he get rid of the beer samples? Leike adds, "of course, I drank the beer afterwards."[14] However, there is more to head decay than an exponential curve will show.

1. Drainage

As soon as foam begins to form, liquid begins to immediately drain from it.[6] In a simple liquid, such as purified water, the phenomenon is quite simple. However, beer contains dissolved proteins, amino-acids, and myriad molecules together in a homogeneous solution. As the liquid drains, variations in localized viscosity form due to in-homogenous variances of bubble surface proteins. Once the foam has been established and stability achieved, drainage comes into play very little in the decay. The rate of liquid removal from a foam is given by:

$$Q = \frac{2\rho g q \delta}{3\eta} \tag{3}$$

Where Q is the flowrate (m^3s^{-1}), η is the viscosity of the film liquid, ρ, the density, q, the length of the Plateau border (m), g is the acceleration due to gravity and δ is the film thickness in metres.[6] The Plateau border is the consequence of the work of Johann Plateau, a belgian physicist who found that soap films always meet in threes, and they do so at an angle of 120 degrees. The resultant edge is called a Plateau Border.[7]

2. Ostwald Ripening

Considerably more well known in the realm of geology, Ostwald ripening is the growth of larger crystals from those of smaller size which have a higher solubility than the larger ones. Also known as disproportionation, this is also directly applied to bubbles; smaller bubbles will form larger bubbles to spontaneously reach greater energetic stability. Small bubbles nucleate far easier than large bubbles, and as such are more *kinetically* favoured. Larger bubbles, however, are more *thermodynamically* favoured as they have a greater volume to surface area ratio than do small bubbles[10].

Why then do these two types of bubbles commonly co-exist in the head of your favourite brew? It is due, quite simply, to the reduction of gas saturation caused by small bubble formationless gas is available to continue the growth of larger bubbles.

Ostwald ripening is governed by the de Vries equation:

$$r_t^2 = r_0^2 - \frac{RTDS\gamma t}{P\theta} \tag{4}$$

Where r_t is the bubble radius at time t, r_0 is bubble radius at the start, R is the gas constant (8.314 J K^{-1}·mol^{-1}), T, absolute temperature (K), D, the gas diffusion coefficient (m^2·s^{-1}), S, the solubility of the gas (mol m^{-3}·Pa^{-1}), γ, the surface tension, t, time (s), P, pressure, and θ, the film thickness between bubbles. Film thickness can be described as the *wetness* of the foam.

Research performed by C. W. Bamforth [6] illustrates that, when comparing carbon dioxide and nitrogen, N_2 wins out in foam stability. Looking at Table I, it shows the effects of gas type and temperature on the bubble diameter over time. Nitrogen gas displays a much slower rate of disproportionation than does CO_2. The head then maintains it's bubble size distribution for a longer period of time (as can be witnessed by the creamy, long-lived head of a pint of Guiness). Unfortunately, nitrogen affects the flavouring of the beer in large quantities, suppressing hop aroma and introducing a syrupy sweetness. This is detrimental to many beers and thus small quantities can be useful to decrease the rate of disproportionation while minimally affecting flavour.

Seconds	CO_2/5°C	CO_2/25°C	N_2/5°C
10	0.49	0.49	0.5
20	0.48	0.48	0.5
30	0.47	0.46	0.5
60	0.44	0.44	0.5
180	0.32	0.30	0.5
240	0.23	0.19	0.5
300	0.03	-	0.49
600	-	-	0.49

TABLE I: The size attained by a bubble (r = 0.5 mm; film thickness 100 μm) after different time periods in the presence of either carbon dioxide or nitrogen and at different temperatures[6].

V. CONCLUSION

From the information stated above, what can be concluded to enhance the appearance and quality of beer foam? First, nucleation sites must be abundant and on the order of 100nm, in order to form small, attractive, stable bubbles, regardless of dispensing methods. Highest reasonable gas content should be used in order to promote the creaming and bubble activity within the beer. A high protein content should be available, such that the beer foam maintains high stability, and furthermore, Nitrogen used to some extent in the dispensing, to further reduce disproportionation.

In-depth knowledge of the intricacies of beer is not required to pour a perfect pint and understanding what goes on can only help expedite the learning process. The theory and equations governing these properties of beer foam are not foreboding. Knowing these, along with learning how the specifics of each type of beer affects the pour, can help achieve repeatable, attractive results with every glass.

[1] B. B. Company. The history of beer, 2003.
[2] E. Tesoro. The history of beer, 09 2003.
[3] C. H. Foundation. Carl von Linde, 2005.
[4] R. Kingsley. re: Why does beer foam less when a glass is tilted?, 1999.
[5] R. Geoffroi. How to pour a beer.
[6] C. W. Bamforth. The relative significance of physics and chemistry for beer foam excellence: Theory and practice. *Journal of*

the Institute of Brewing, 110(4):259–266, 2004.

[7] Wikipedia. Plateau's laws, April 2006.

[8] A. D. Ronteltap. *Beer foam physics*. PhD thesis, Agricultural University, Wageningen, 1989.

[9] P. Weiss. The physics of fizz: Toasting a burst of discovery about bubbles in champagne and beer. *Science News*, 157(19):300, May 2000.

[10] T. Bergfors. Tutorial 6: Ostwald ripening.

[11] Stanford. Heading to physics through a beer glass, darkly. URL, 1991.

[12] B. Wolf. Weird news: A look at the Ig Nobel Prize, September 2002.

[13] Wikipedia. List of Ig Nobel Prize winners.

[14] physicsweb. Beer paper wins Ig Nobel Prize, October 2002.