The Physics of BEER:

Basic Fluid Mechanics of Bubbles and Foam – Getting the Right Amount of Head!

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Introduction…… TO BEER!!!!!

Some Properties of Beer and their Importance:

- Carbonated Bubbles versus Frothy Foam
- “Fizzy or Foamy”

How you like it depends on the beer and on your preference:

Beer drinker 1 (a Belgian?)		
“Lively beer with good head”	“Flat beer”	“Great lacing, top beer!”
Beer drinker 2 (a Londoner?)		
“Ripped off, foam is not beer!”	“That is more like it, a full measure of beer”	“A dirty glass”
Beer drinker 3 (a Lady?)		
“Will this foam stick to my lip and wreck my make-up?”	“Not very lively and appealing beer”	“This glass has not been properly cleaned before filling”

Different Beer Types have different fluidic properties such as density (includes sugar content), carbonation and other gas content, surface tension, viscosity, etc…

Let’s look at some of these properties with examples:

- Density: the mass per volume of beer
  - ➔ Typically range from 1.000 – 1.025 (relative to water density)

- Surface Tension: force per unit length of any arc on a curved surface between two liquids due to a relatively stronger cohesion of molecules of one fluid.
  - ➔ Beer is typically around 42-48 mN/m, whereas pure water is 73 mN/m (see [2]). It can be quite different from that of water mainly due to alcohol not being as polar and influenced by hydrogen bonding as water molecules…
  - ➔ The more ‘cohesive’ fluid pushes back.

➔ This can allow some 'denser' insects to float on water, or bubbles of gas to form, like gas in a stretched balloon…

■ Viscosity: the property of a fluid to 'pull' on nearby fluid due to attraction between fluid molecules.

➔ Typical values in beer can range from 0.0010 – 0.0020 Pa s

- We see that although most beers have different densities, viscosities, etc… they are all well within an order of magnitude within each other

Now what about all those bubbles and foam!!!????

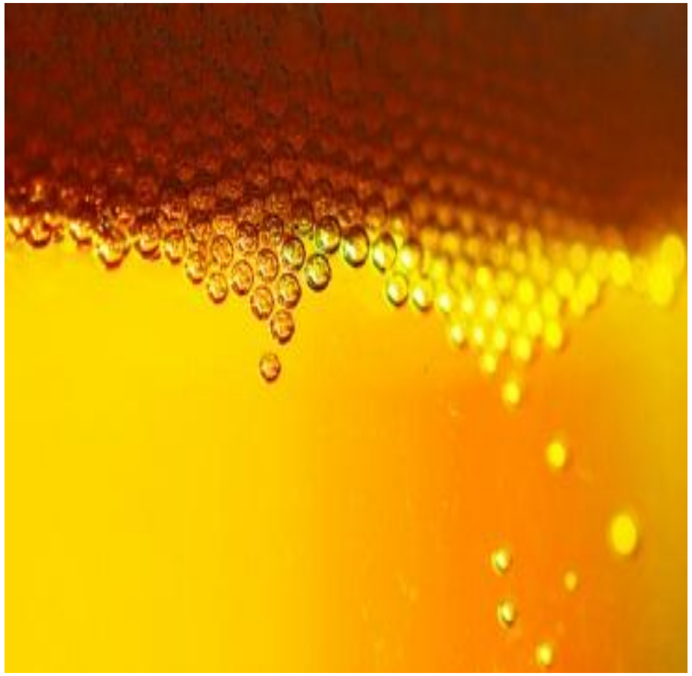
- The actual physics of beer can be quite complicated, and has only recently been slightly (although not nearly fully) understood theoretically! (See references [1] and [2] for example)
- Even savvy Beer Experimentalists (Any of you here? ;))
  know of the difficulty of beer pouring…

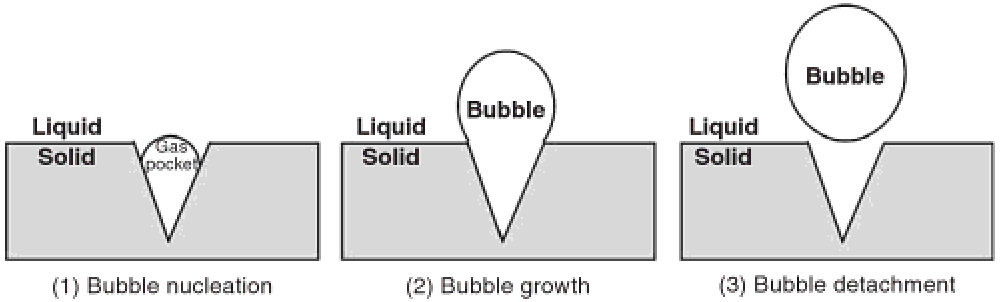
So let's start by looking at bubble formation (nucleation):

BUBBLES and their Physics

Bubbles of a fluid/gas in another fluid due the surface tension of the surface of separation

- Knowing just these basics let's derive bubble nucleation in beer!
  FIRST: Bubbles must be formed at a nucleation site (unsmooth edge of glass, floating particle, etc… [1]) and their size depends on the characteristic size of the nucleation sites R_m





Then balancing surface tension and gravity we easily derive the bubble radius:

$$\text{Bubble radius} = \left[\frac{3R_m\gamma}{2\rho g}\right]^{1/3}$$

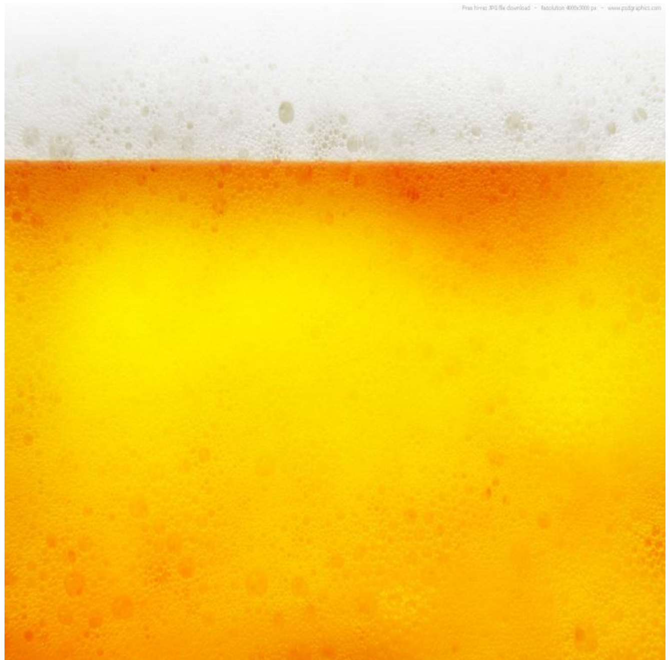
where
R_m = radius of nucleation site (m)
γ = surface tension ($mN\,m^{-1}$)
ρ = relative density of the beer ($kg\,m^{-3}$)
g = acceleration due to gravity ($9.8\,m\,s^{-2}$)

We can also use Stoke's formula to find the velocity of rising gas bubbles to determine a rate of growth of the beer 'head':

$$v = \frac{2g\rho r^2}{9\eta}$$

Let us calculate this together as a basic balance of viscous damping to buoyancy…
(see, e.g. Landau and Lifschitz, Fluid Mechanics…)

It turns out that this so-called 'creaming' of bubbles due to them rising to the top is quite

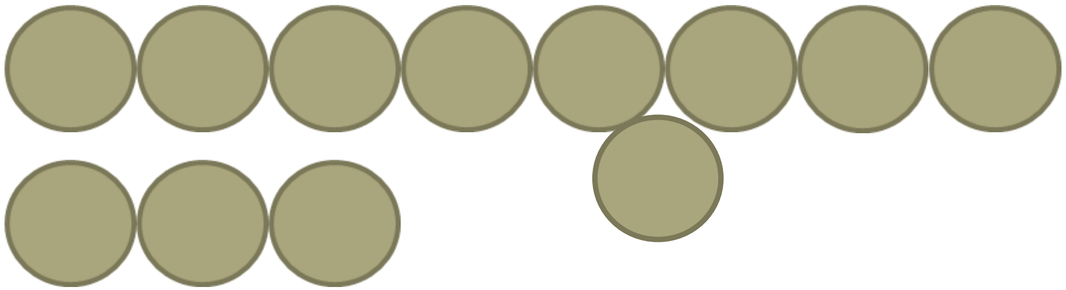


insignificant (as it is faster – calculate this!!!) in comparison to the rate of nucleation itself [3].
- So we require some further knowledge of rate of nucleation and number of nucleation sites and their characteristic sizes we can attempt to understand rate of formation and even amount of beer 'head' obtained after a certain pouring velocity!!!

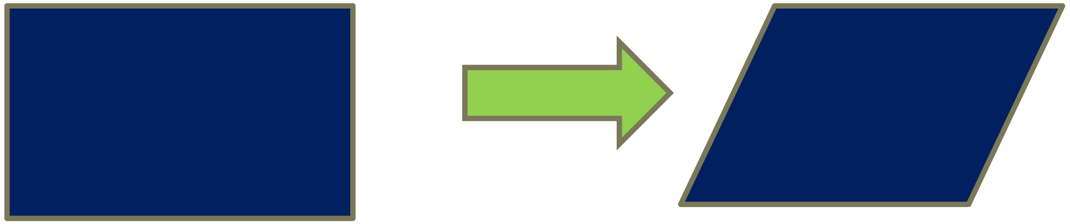
This however takes some more work and is not yet fully understood, and some knowledge of chemistry can be quite necessary [3]

FOAM and its Physical Properties

Foam can take on certain solid-like properties due to the surface tension of stacked bubbles composing it:



This can give the foam properties (moduli) of shear and stress:



- Let's do a calculation as an example: <u>The 'Stiffness' of beer foam</u>

  Now what about that foamy beer head???

Here's how it works putting what we've all done so far together:

- Nucleation of bubbles (first thing we calculated)
- Creaming: the bubble rise (just calculated). It is around 0.1 to 0.4 cm/s and is found to not be the most significant.

- Disproportiation [3]: The bubbles decrease in size over time thermodynamically, by gas diffusion, and thinning of bubble films.

 Let's see how it does this by looking at the D' Vries equation:

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

where
r_t = the bubble radius at time t
r_0 = bubble radius at the start
R = the gas constant (8.3 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
θ = the film thickness between bubbles

--Some experimental results show in the table below will give a hint to the importance in this effect in decreasing foam volume over time:

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.

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	0.3	0.5
240	0.23	0.19	0.5
300	0.03	—	0.49
600	—	—	0.49

*It turns out [3] that fusion (coalescing) of bubbles is not near as significant as this found due to disproportiation.

Finally the fourth step is…

- Drainage: the decay of the beer foam due to liquid draining from the foam head

Let's try to make sense of this standard formula we have no time to derive:

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

If we had time we could easily derive the change in film thickness over time from this!

$$t(\delta) = \frac{6\eta h}{\rho g \delta^2}$$

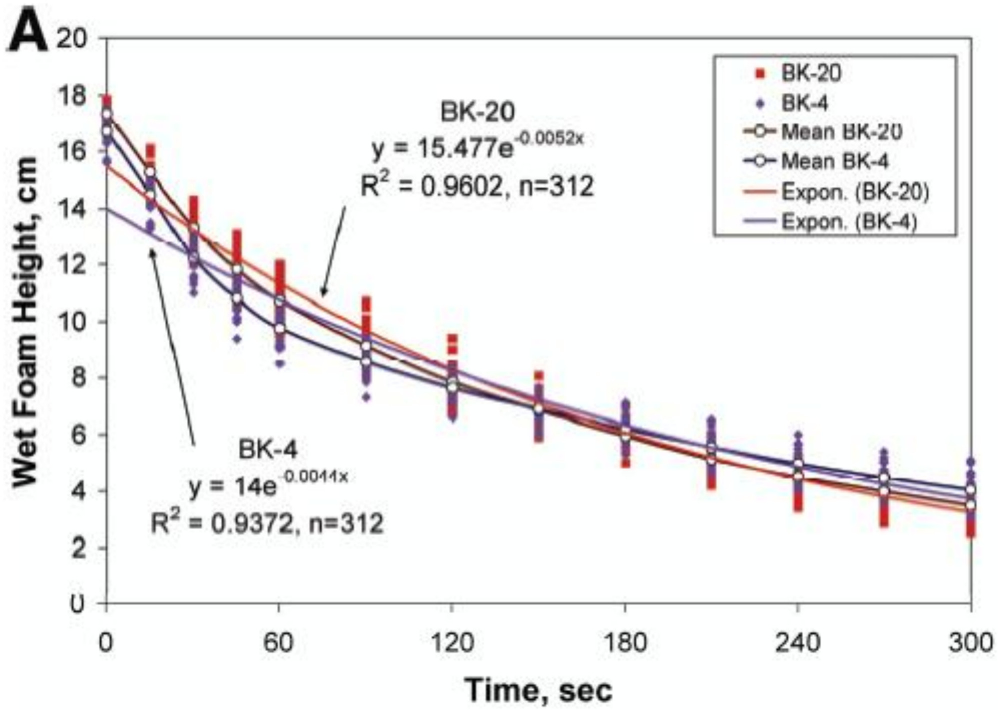
Homework Problem!

➔ ALTOGETHER this leads to foam formation and to the observed exponential decay of beer foam [2].

We discussed above the formation of bubbles and attempted to explain rate of head formation, but what about the decay of the head we observe???

- It turns out to be exponential!

Some results from the paper [5]:



BUT THIS ISN'T NEARLY THE FULL STORY!!!!

We still have lots more to know about this complicated thing called BEER and of its chemistry…

➔ The importance of the chemistry of beers on foam formation (see [2]). This includes the role of proteins and albumin in nucleation and extensive research has recently been done [2].

We can also examine the dynamics of FLOW of beer (TIME PERMITTING!):

Let’s take up a bit of fluid mechanics first!

A good way to do this is to know a universal property of a certain fluid’s flow -- the Reynold’s number, a dimensionless quantity:

*All fluid flows with similar Reynold’s number exhibit similar properties, regardless of what fluid!

Examples: Let's do some calculations!

1. High-speed Car versus smaller model in a wind tunnel
2. Swimming in syrup versus water! How is it different? (Example: the Spermatazoa versus the tadpole)

Homework Problem: Derive equations for the velocity of movement of a tadpole 'flapping' in water, versus that of a sperm cell 'tail wirling' (like a helix just discussed above) and prove that this is the best way for them to swim within their respective flow's Reynold's numbers.

If you do then……….

Thanks for Listening!

Conclusions:

- The presence of bubble nucleation sites (such as scratches, impurities, microbubbles from vortex formation, etc…) should be made small as possible and as uniform so as to reduce excess foam production and to made it as uniform and stable as possible to reduce the effect of disproportiation
- The effect of creaming (bubble rise) supplies continuously bubbles for the foam, however the effect of disproportiation is the most significant to foam growth and stability
- Drainage of liquid from foam is the most responsible for the decay of the foam however much more is going on here due to viscosity variations of foam over time and film thickness variations…

- Much more needs to be understood and the chemical side of things is very important, with much studied in regards to various non-lipid (like protein, polymer, albumin, etc…) concentrations [2].

Questions???

References:

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[4] M. Denny, Froth!: the science of beer (Johns Hopkins University Press, Baltimore, 2009) 1st. ed.

[5] J. Harkbarth, The Exponential Decay of Beer Foam Stand.
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