Method of Analysis for correcting dissolved CO2 content for Specific Gravity and Alcohol variations in beer

"Creating a Dynamic Henry's Law Equation"

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Abstract

This article will describe required updates to the ASBC Methods of Analysis to better match Henry's Law calculations with Beer-Lambert's Law used in spectroscopy and infrared instruments.

Dissolved carbon dioxide is a molecule that vibrates and has a mid infrared absorption band in the electromagnetic spectrum at 4.27 microns. Using Beer-Lambert's Law, precise concentration measurements can be determined using reflective spectroscopy -specifically Attenuated Total Reflection (ATR).

This article will report results of studies showing flaws in the current Henry's Law method for measuring concentration in beer and present updated formulas to make CO2 content in beer consistent with stated instrument accuracies.

Introduction

The traditional Method of Analysis for measuring carbonation in beer uses a modified version of Henry's Law, converting pressure and temperature measurements to concentration of CO_2.

$$\text{VolumesCO2} := \frac{4.85(\text{psi} + 14.7)}{\text{Farenheit} + 12.4}$$

Equation 1.0

Equation 1.0 is published in "A Handbook of Basic Brewing Calculations" by Stephen R. Holle. This method uses a single constant in the Henry's Law equation for solubility, an assumption of 1.01 specific gravity and no correction for atmospheric pressure making the method outdated and inaccurate.

The use of Henry's Law to calculate CO2 content is an indirect method which does not measure the concentration of any individual gas but the composite result of all dissolved gases. In recent years, changes in the beer industry product formulations have exacerbated these flaws. Out of necessity, density was introduced as a constant in the Henry's Law equation because pressure -temperature instruments do not measure density at all. Historically, the Henry's Law method evolved with the assumption that all beer had comparable density, a specific gravity of 1.015 and an alcohol content of 3.8% by weight.

Light beers, ales and low carbohydrate beers have rendered the assumption that all beers have comparable density to be incorrect. In fact, many beers now have a lower specific gravity than water. The use of nitrogen in many beers to give a richer head makes using temperature and pressure to measure dissolved gas inaccurate, both because of the lack of differentiation in the gases and because of the differences in the solubility coefficients. Beer with different alcohol contents has a different density. Additionally, the introduction of high speed bottling lines and dynamic tank changes in today's modern breweries cause pressure spikes which are unrelated to carbonation. This causes apparent concentration spikes in pressure-temperature based instruments.

This paper proposes an update to the Henry's Law model that will make pressure-temperature lab methods better correlate to ATR based infrared online measurements that measure CO2 content directly. The updated model will remove the distortions caused by pressure spikes, membrane deterioration and maintenance thereby making comparisons between infrared data and historical data more relevant.

Updating Henry's Law Calculations

Henry's Law equations for beer have not been significantly updated since they were introduced in "Methods of Analysis" American Society of Brewing Chemists 5th Edition-1949. At that time, charts were introduced based on empirical data that converted Henry's Law equation for water to an equation for beer. Because of the unavailability of computers, constants were determined for many variables that today are straightforward to store as variables. These include alcohol content, specific gravity and atmospheric pressure.

The paper, "A compilation of Henry's Law Constants for Inorganic and Organic Species of Potential Importance in Environmental Chemistry" gives the relevant equation for determining solubility coefficients for gases in fluids.

$$k_{H,INV}=p_g/x_a=Q_{liq}/(M_{liq}xk_H)$$

Where: $K_{H,INV}$=volatility
P_g=partial pressure gas phase
X_a=molar mixing ratio
Q_{liq}=Density of liquid
M_{liq}=Molar mass of liquid
k_H= solubility of gas in liquid

Equation 2.0

Equation 2.0 provides the basis for an important update to the Henry's law equation for CO_2 concentration. It states that Henry's Law constants are proportional to fluid density. To test Henry's Law a different method must be used. Beer-Lamberts law is used by infrared sensors which measure the vibrational spin of the CO_2 molecule.

Since there are specific Henry's Law constants for CO_2 concentration in water it makes sense to compare CO_2 concentration levels using both methods in water.

Beer-Lambert vs Henry's Law R^2=.9997

Graph 2.0

Beer-Lamberts vs Henry's Law in Water
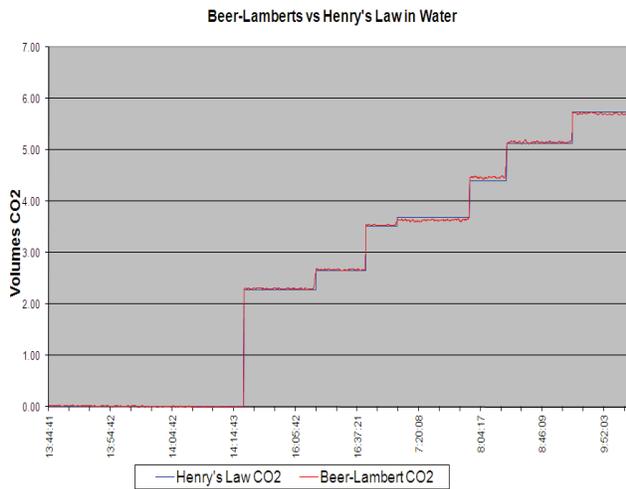
Graph 1.0

For Graph 1.0 Henry's Law CO2 concentration data was taken using absolute pressure and temperature. The Beer-Lamberts concentration was taken using a VS-3000 inline infrared sensor. Graph 2.0 shows an X-Y scatter plot of actual data showing an R^2 regression of 0.9997 proving method equivalence.

At this point it should be understood that Henry's Law is applicable for Beer when the process environment is constant. This is to be expected. However, today's dynamic process environment with varying beer and brand types makes the historical implementation of Henry's Law by pressure-temperature instruments outdated.
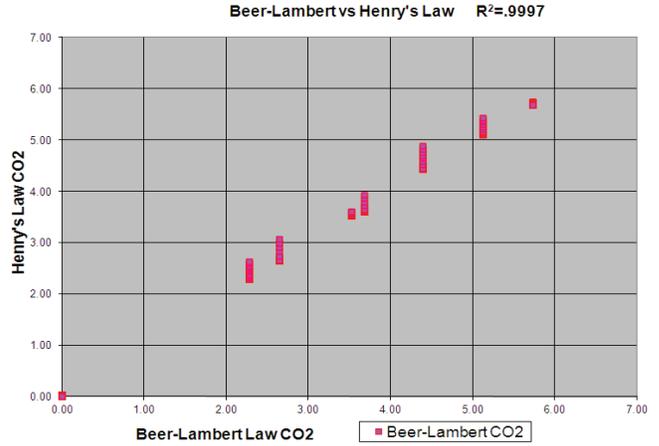
A Dynamic Henry's Law Equation

Today's modern instruments and systems make it possible to more accurately calculate and update Henry's Law for Beer. First we know that solubility is inversely proportional to density and ethyl alcohol has a density of .789 g/ml versus 1 g/ml for water. The second update is for specific gravity. The current ASBC method asks for a correction proportional to specific gravity. The current ASBC chart also suggests a correction for atmospheric pressure of 1PSI for every 2000 ft above sea level. If we take the current Henry's Law equation and add these as dynamic variables we get the following equation.

$$Volumes\_CO2 := \frac{5.16\cdot(psi+\text{Baropressure})}{(\text{Farenheit}+12.4)\cdot SG\cdot\left(1+\frac{1}{.789}ABW\right)}$$

Where:

Volumes= CO2 volume/volume
PSI=Gauge pressure
Baropressure = Barometric Pressure PSIA
Farenheit= Fluid Temperature Farenheit
SG=Specific Gravity
ABW= Ethanol (w/w%) ie: 3.6%=.036

Equation 3.0

To make this equation easy to use VitalSensors Technologies has created a software calculator for the ASBC that uses this formula. To take current online pressure-temperature measurements and convert them to the updated Dynamic Henry's Law equation the following formula can be used.

$$TrueCO_2 = \frac{5.16 \times (GP + BP)}{(T + 12.4) \times SG \times \left(1 + \dfrac{E}{0.789}\right)}$$

Where:

$TrueCO_2$	– True Carbonation (CO_2) in **v/v**
GP	– Gauge Pressure in **psi**
BP	– Barometric Pressure in **psia**
T	– Temperature in **°F**
SG	– Specific Gravity
E	– Ethanol in **w/w**
5.16	– Henry's Law Water Constant
0.789	– Density of Ethanol

Equation 4.0

Application

      To determine if this formula is correct, data was collected over several days and several beer brands using a VS-3000 dissolved CO2 inline infrared instrument using Beer-Lamberts' Law and comparing it to an online pressure/temperature instrument using Equation 4.0. An online density meter was used to measure Alcohol and Specific Gravity. The data is shown on Graph 3.0
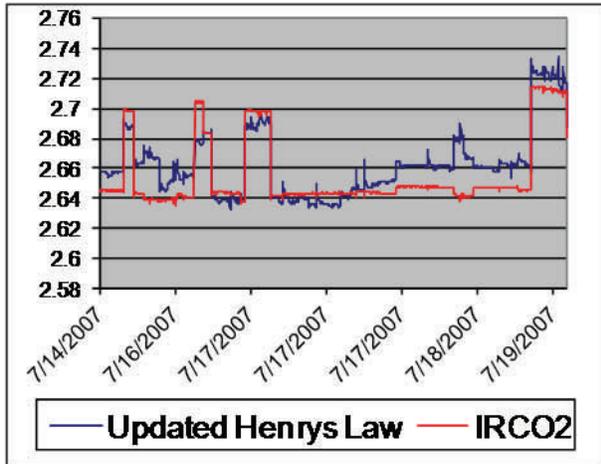
Graph 3.0

The data matches to the stated measurement accuracy of the pressure-temperature instrument. Note that data with pressure spikes was removed from the pressure-temperature instrument to improve its accuracy and repeatability. The Beer-Lamberts Law data is depicted as IR CO2. The Updated Henry's Law data is depicted as Updated Henry's Law. A further improvement could be made if real time Barometric Pressure data were available and the formula included Barometric Pressure. The pressure-temperature device was calibrated using a Haffman's Gehaltameter with an absolute pressure meter to

minimize this error. The graph shows that the Beer's Law infrared sensor data is more repeatable. Part of this remaining Henry's Law error could be due to changes in atmospheric pressure, using an absolute pressure sensor would solve this. To dynamically match infrared to simplified pressure temperature data an inverse correction can be used to "distort" the infrared reading to match historical charts. By algebraic manipulation

$$IRCO2PT_i := \frac{4.85}{5.16} \cdot \frac{IRCO2_i}{(SG_i)} \cdot \left(1 + .789 \cdot ABW_i\right)$$

Conclusions

      The current ASBC method for Henry's Law determination of CO2 volumes in beer is inaccurate. This paper uses dynamic variables for specific gravity and alcohol to make the equation more accurate. When this is done Henry's Law method for CO2 measurement in beer matches Beer-Lamberts Law method to the measurement accuracy of the pressure-temperature instrument over several beer brands with different specific gravity and alcohol content.

      Implementation of the Dynamic Henry's Law Equation allows breweries the potential to align and compare current and historical process pressure-temperature CO2 data to inline infrared instruments.

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