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Mathematical Modeling of Beer Foam

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ABSTRACT

Foam collapse times and a number of different chemical components were measured on a variety of bottled beers from throughout the world. The data were analyzed for either simple correlations or mathematical models were built using multiple regression or neural network analyses. The models constructed explained 89% of the variation observed in foam collapse and included only IBU, pH, real extract, and high molecular weight protein. Simulated experiments were performed using fractional factorial experimental designs and response surface models developed from the results.

SINTÉSIS

Tiempo de colapso de la espuma y otros varios componentes fueron medidos en una variedad de cervezas embotelladas provenientes de todo el mundo. Los datos fueron analizados por su simple correlación o se construyeron modelos matemáticos simples usando regresión múltiple o análisis simple de red. Los modelos construidos explicaron un 89% de las variaciones observadas en el colapso de la espuma e incluyeron solo IBU, pH, extracto real, y proteína de alto peso molecular. Experimentos simulados fueron hechos usando diseños de experimentos por fracción factorial y modelos de reacción de superficie fueron desarrollados de los resultados.

INTRODUCTION

Foam is one attribute of beer used to judge its quality. Beer foam is a complex phenomenon that is the result of the interaction of a large number of factors. A number of beer components have been identified that either contribute to increased stability (foam-positive factors) or to reduced stability (foam-negative factors.[4,7,11,12] Because these can vary greatly in different styles of beers, foam stability varies over a wide range. The factors can be classified into three groups:

1. Proteins/Polypeptides

Increased levels of proteins (or specific protein fractions) have been associated with better foam.[3,5,13] Both high molecular weight and low molecular weight fractions as well as hydrophobic proteins have been reported to affect foam either positively or negatively.[6,17] The protein content of beer is widely believed to be the necessary backbone for acceptable foam stability.

2. Isoalpha Acids

The amount of isoalpha acids, which are derived from isomerization of hop alpha acids during the kettle boil, has a strong influence on beer foam.[2,3]

3. Other Factors

A number of other factors, including viscosity-increasing compounds such as beta-glucan and dextrins, pH, lipids, middle-chain-length fatty acids, melanoidins, and alcohol content, have been reported to affect foam.[8,9,14,17,18]

The objective of this study was to identify the beer components or measurable attributes that are most responsible for the observed variability in the time for foam collapse in a standard test. To achieve this objective we applied single factor statistical correlation and two mathematical modelling techniques to data from a large number of different beers.

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EXPERIMENTAL

Forty nine beers from breweries around the world were analyzed for foam collapse time and the following parameters:

- Original Gravity (OG)
- Real Degree of Fermentation (RDF)
- Alcohol
- Bitterness (IBU)
- High Molecular Weight Protein (HMWP)
- Real Extract (RE)
- Specific Gravity (SPGR)
- Color
- Isoalpha Acids (IAA)
- pH

Foam Measurement

An automatic pour machine was used to evaluate the foam of the beers. This machine (Fig. 1) reproducibly pours a beer into a glass simulating a consumer-use situation. The reproducibility of this technique enables even small differences in foam to be detected. Foam collapse time, the measure of foam stability we used, was defined as the time taken for the foam to collapse 1.5 inches below the lip of the glass. All beers were adjusted to 2.7 ± 0.1 volumes of CO_2 and equilibrated to 40°F before pouring.

Analytical Measures

High molecular weight protein was determined by a modified Bradford method described by Löffler and Kunze.[10] Isoalpha acids were determined by an HPLC method based on Ono *et. al.*[15] Other measures were determined by standard ASBC procedures.[1] Beers that were known or found to contain foam enhancers, such as tetrahydroisohumulones or propyleneglycol alginate, were excluded from the data set.

DATA ANALYSIS

Three methods of analysis were used to determine which factors were important in explaining the variation seen in the beers.

1. Single Factor Linear Correlations

These are correlations between single factors and foam. A single factor that explains a large amount of variation will have a high coefficient of determination (R^2). Multiplying the R^2 by 100 gives the percent variation explained.

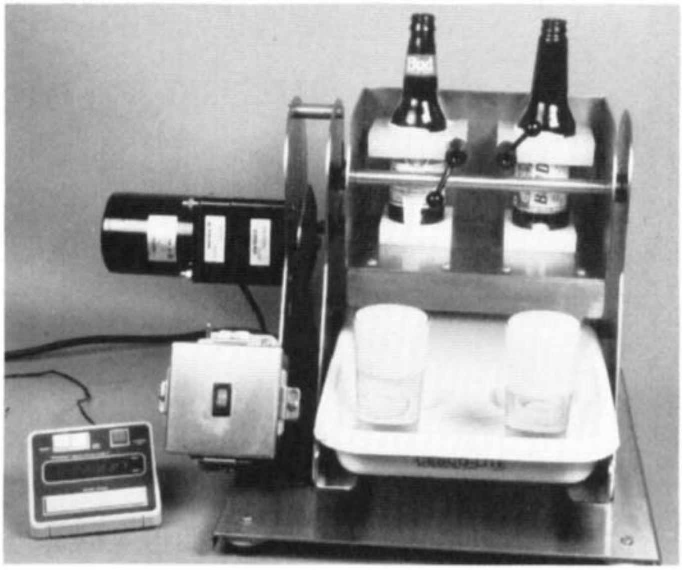

Fig. 1. Automatic pour machine used to determine foam collapse time.

Fig. 2. Foam collapse times measured for 49 beers. Range of values from 2.9 to 7.0 minutes.

2. Multiple Regression Analysis

This is a method for developing polynomial algebraic equations that reflect the relationships between an observed result and a number of measured factors. The components of the equation can be either simple linear terms, interactions between two variables, or quadratic terms. The models were developed using forward, backwards, and stepwise selection. Both single factor correlations and multiple regression analysis were performed using the SAS statistical software program (SAS Institute Inc., Cary, NC 27513).

3. Neural Network Modeling

Neural network technology is a pattern recognition system that attempts to classify patterns according to other learned patterns. The computer software functions similarly to a biological neural network. The network is composed of several layers of simulated neurons each of which processes a number of inputs to produce an output.

The neural network is constructed using a learning set of data, which is a subset of the full data set. During the learning process the connection weights between the neurons are modified to minimize the error between actual and predicted outputs. The network is then tested periodically against the test set of data, which is the remaining subset of data. The network that gives the best agreement between actual and predicted outputs on the test set data is retained. This data analysis was performed using Neuroshell software (Ward Systems Group, Inc., Frederick, MD 21702).

Response Surface Models

Fractional factorial designs for the simulated experiment were developed using the Optimization software program (Int'l Qual-Tech, Ltd., Minneapolis, MN 55447).

RESULTS AND DISCUSSION

The beers varied widely in all the chemical attributes measured (Table 1). Foam collapse times of the beers tested ranged from 2.9 to 7.0 minutes and were fairly uniformly spread over the range (Fig. 2).

Single Factor Correlations

The factors are listed in Table 2 in the order of their ability to individually explain variation in foam collapse. IBU was the single factor that explained the most variation in foam collapse. Notably, pH explained the smallest percentage of variation, although it proved to be a very important factor in building the following models.

Multiple Regression and Neural Network Models

In both types of models the three most important factors are IBU, pH, and real extract and the models explained 87% of the foam variation observed. Addition of high molecular weight pro-

Table 1
Range of Chemical Attributes in Beers Analysed

Attribute	Low	High
Original Gravity (OG)	7.66	18.05
Real Extract (RE)	1.77	8.31
Real Degree of Fermentation (RDF)	49.5	81.0
Specific Gravity (SPGR)	1.000750	1.023480
Alcohol (% V/V)	3.76	7.29
Color	2.2	131.8
Intl. Bitterness Units (IBU)	7.0	40.0
Isoalpha Acids (IAA) (in ppm)	8.4	50.7
pH	3.83	4.74
High Molecular Weight Protein (HMWP) (in mg/L BSA equivalent)	127.4	938.1

Table 2
Single Factor Correlations Between Collapse Time and Chemical Factors

Factors	Correlations (+/−)	% Collapse Variation Explained (R^2 As %)
IBU	+	63.9
OG	+	45.2
IAA	+	41.5
RE	+	39.4
HMWP	+	35.0
SPGR	+	33.7
Alcohol	+	29.3
Color	+	29.0
RDF	−	27.6
pH	−	9.7

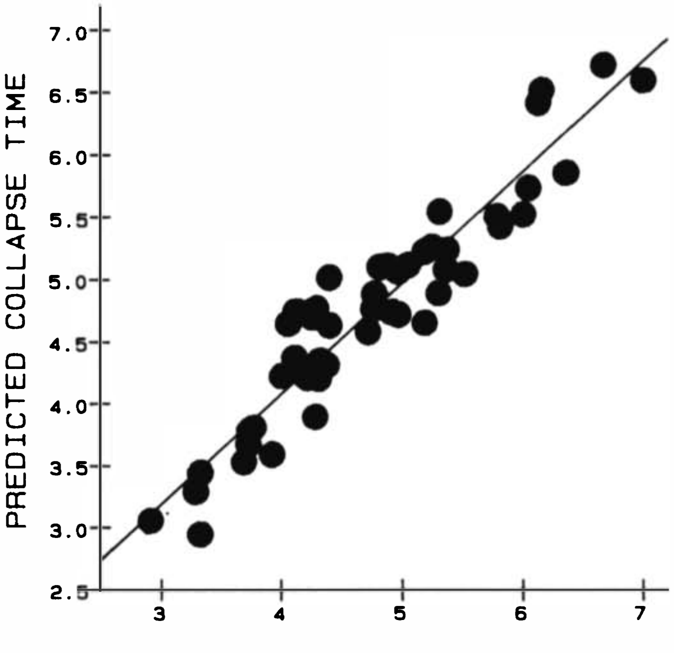

Fig. 3. Actual collapse times vs. collapse times predicted by multiple regression model (R^2 = 0.8927). Facters included: IBU, pH, RE, HMWP.

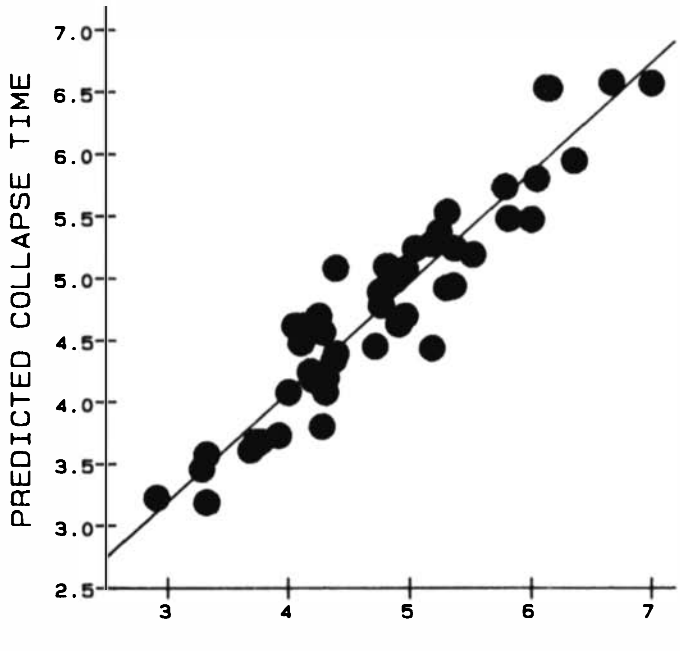

Fig. 4. Actual collapse times vs. collapse times predicted by neural network model (R^2 = 0.8905). Facters included: IBU, pH, RE, HMWP.

tein to the model increased the variation explained slightly to 89% (Figs. 3 and 4).

The relative importance of individual factors to the percent of variation explained by a model can be determined by comparing the R^2 values of models with and without the factor. In this way we were able to show (data not included) that although pH showed an extremely poor single factor correlation with foam, it was consistently the second most important factor in the models. Including pH as a factor improved the R^2 values for models more than any other factor except IBU.

IBU is a nonspecific measure of the hop compounds in beer while IAA is a very specific analysis for isoalpha acids, the major foam stabilizing hop compounds. However, it was noteworthy that IBU was a better predictor of foam, both as a single factor and in the models. IBU analysis measures oxidation products that may be foam-active as well as isoalpha acids and this may explain why it is a better measure. Similarly, RE is a nonspecific measure of beer soluble solids including proteinaceous material and carbohydrates, while HMWP is a more specific measure of protein material with a molecular mass greater than 5000 daltons. Including HMWP with RE in the models only slightly improved the models. The lesser relative importance of protein suggests that, although protein is undoubtedly a necessary ingredient for good beer foam, it is not usually a foam-limiting component.

Understanding the Models

We had two choices in trying to understand the underlying interactions between components in the mathematical model: (1) either test the model by brewing beers having different combinations of the key factors or (2) simulate experiments using the model. As it is difficult to simultaneously and precisely control several of the key factors when brewing beers, we decided to simulate an experimental design allowing the model to predict the results. This was very simple to do and it revealed how the key components interacted in the model. However, it is important to note that this simulated experiment did not validate the model in the way a true experiment would have.

The simulated experimental design was done using a central composite fractional factorial design. The experimental trials were simulated by entering the desired experimental conditions into the mathematical models and recording the model's responses. These results were then entered into the Optimization software program and response surface models developed. Here we will show two examples of the response surfaces from the simulated experiment using the neural network model.

Effect of IBU and pH on Foam Collapse

Figure 5 shows that increasing IBU or decreasing pH will result in longer collapse times at any level of real extract. At the lower HMWP levels the increase in collapse time produced by increasing IBU or decreasing pH is larger than that produced at higher HMWP levels. This means that in beers with lesser amounts of HMWP changing the IBU or pH has a significant effect on foam collapse time. Conversely, changing the IBU or pH of a beer with a high HMWP has only a small effect of its collapse time.

Increasing HMWP also will result in longer collapse times at any combination of IBU and pH. The change in collapse time is large at high pH or low IBU or both. Conversely, the increase will be very small in beers with either very high IBU or very low pH or both.

Effect of pH and HMWP on Foam Collapse

The response surfaces in Figure 6 show that increased HMWP or lower pH results in longer collapse times at any level of IBU. At the lower IBU levels the increase in collapse time produced by increasing HMWP or decreasing pH is larger than that produced at higher IBU levels. This means that in beers with low IBU changing the pH or HMWP has a significant effect on collapse time. Conversely, changing the pH or HMWP of a beer with high IBU has a much smaller impact on collapse time.

Increasing IBU will result in longer collapse times at any com-

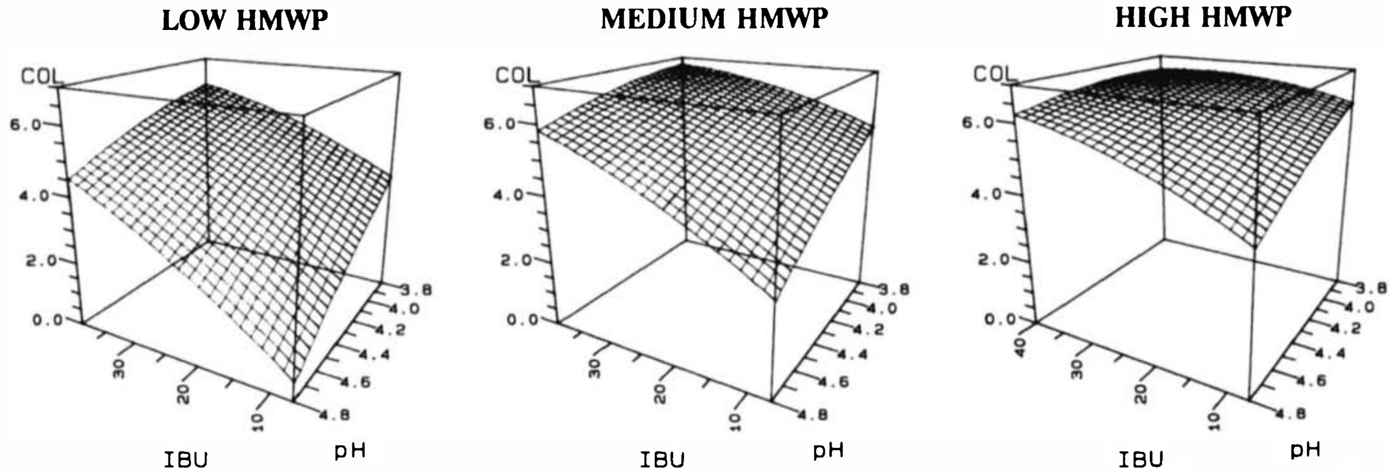

Fig. 5. Response surfaces for effect of IBU and pH on foam collapse at low (127 mg/l), medium (533 mg/l), and high (938 mg/l) levels of HMW protein, all at medium level (5.0 g/100 ml) of real extract.

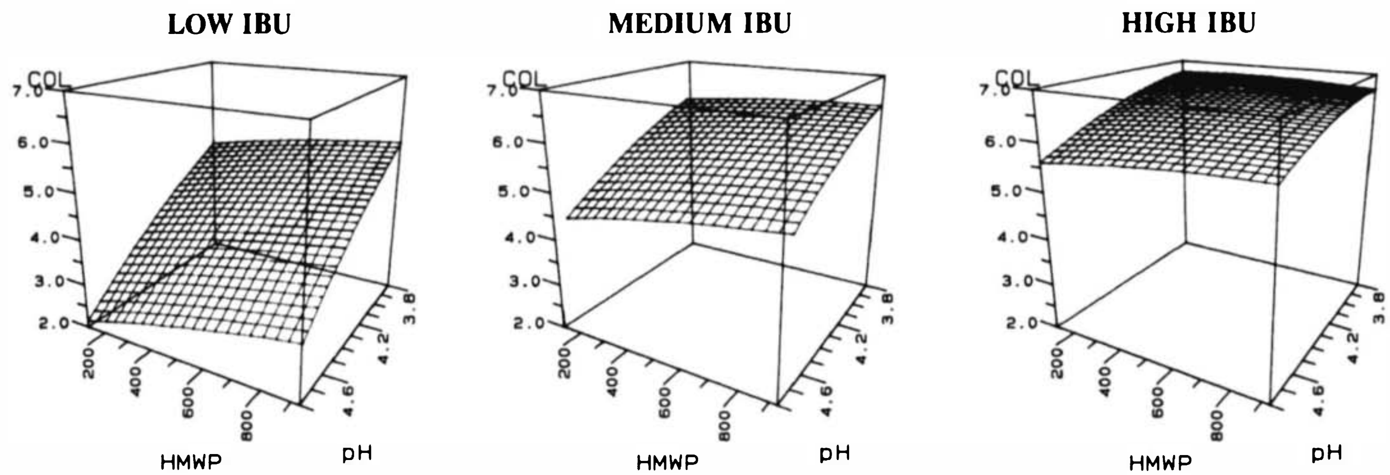

Fig. 6. Response surfaces for effect of pH and HMW protein on foam collapse at low (7.0), medium (23.5), and high (40.0) IBU, all at medium level (5.0 g/100 ml) of real extract.

bination of pH and HMWP. The change is largest at high pH or lower HMWP or both. Conversely, the increase in foam collapse time caused by increased IBU will be small in beers with either low pH or high HMWP or both.

Using only four beer components models can be built that explain the majority of the variation seen in the foam collapse of a wide variety of beers. The models that were developed can have two types of use: (1) to enable the brewer to be able to diagnose and solve foam problems rapidly and (2) to assist in the development of new products. From formulations it is possible to estimate the level of the four components and so accurately predict the foam even before brewing. Adjustments can then be made to the formulation so optimal foam will be attained in the first trials.

SUMMARY

Forty nine beers from throughout the world were analyzed for foam and chemical composition. Mathematical models, which explain a large amount of the variation seen, were built from the data. The models identified the most important factors (in order of importance) as: (1) IBU, (2) pH, (3) real extract, and (4) high molecular weight protein. Response surface models were built from simulated experiments and revealed relatively simple relationships between the most important factors. Foam is better on beers with higher IBU, real extract, and high molecular weight protein and lower pH.

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