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Fate of ethanol during cooking of liquid foods prepared with alcoholic beverages: Theory and experimental studies

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ABSTRACT

To obtain an understanding of the ethanol loss during cooking of liquid foods containing alcoholic beverages, ethanol concentration was measured as a function of time and remaining volume in meat stocks prepared with wine and beer. A mathematical model describing the decline in volatile compounds during heating of simple liquid foods was derived. The experimental results and the model show that concentration of ethanol at any given time is determined by the initial concentration and a power law function of the remaining volume fraction. The power law function is found to be independent of factors like pot dimensions and temperature. When using a lid to cover the pot during cooking, the model was still valid but the ethanol concentrations decreased more steeply, corresponding to a higher exponent. The results provide a theoretical and empirical guideline for predicting the ethanol concentration in cooked liquid foods.

1. Introduction

Beer, wine and other alcoholic beverages are used for cooking in a range of dishes; particularly they are used as a cooking medium for meat or in a sauce to enhance the flavour. The remaining ethanol amount after cooking is important for correct determination of the energy content of a meal but also important for the consumer who wants to control the consumption of alcohol (e.g., children, drivers, alcoholics). Only few studies have investigated this topic (Augustin, Augustin, Cutrufelli, Hagen, & Teitzel, 1992; Hansen, Kwasniewski, & Sacks, 2012; Helander & Bergström, 2001; Mateus, Ferreira, & Pinho, 2011; Ryapushkina et al., 2016).

In addition to ethanol, food contains other volatile compounds like aroma components and sometimes dissolved gases like oxygen and carbon dioxide. Water, which often constitutes the majority component in foods and acts as a solvent, is also volatile. Heating or boiling food enhances the loss of water and volatile solutes like ethanol. For mainly liquid food, like soups, stocks and stews, components that evaporate faster than water, such as ethanol, will decrease in concentration.

When heating liquid foods the volume most often decreases due to evaporation of water. Simultaneously the flavour and possibly the viscosity change. The kitchen operation 'reduction' refers to the deliberate boiling off water in a stock, which results in an increase in viscosity and a more intense flavour, as studied by Snitkjær, Frøst, Skibsted, and Risbo (2010). The heating operation of liquid foods can be characterized by various parameters like the area of the evaporating surface (pot diameter), temperature and heating power input. The heating power will control the rate of evaporation of water and ethanol in an open cooking pot.

In this paper we raise the question of how the ethanol concentration in liquid foods is affected by heating and to which degree parameters like temperature, pot diameter, the use of a lid, heating power input, liquid volume and cooking time affects the ethanol concentration. Veal stocks are used as the model food and ethanol

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concentrations are measured at various stages during a reduction. Furthermore, a theoretical approached is employed; a simple but general model for the evaporation of water and diluted volatile is derived. The theory and experimental results are compared, leading to a description of ethanol loss of boiling liquids emphasising relevant parameters. The results are generalized to include other volatiles such as aroma components and dissolved gases.

2. Materials and methods

The experimental set up consisted of 47 stock reductions, where veal stock mixed with alcoholic beverage was boiled down for 30 min using different parameters. The experimental series 'base' was carried out by adding brown ale (Jacobsen, Denmark) to the stock and boiling the mixture down in a pot (diameter = 20 cm, height = 12 cm) without a lid. The additional five series of stock reductions were carried out by changing one parameter at a time. The experimental design including experimental parameters for all stock reductions and ID of the individual experiments can be seen in Table 1. Replicates in each experiment are denoted with a letter from **a** to **g**.

2.1. Veal stock reductions and volume determinations

Veal stock was prepared by diluting veal stock concentrate (Bong, Sweden) according to the prescription on the bottle; and alcoholic beverage was then added. The alcoholic beverages included three Carlsberg beers: 1) Jacobsen brown ale 6% (BA), 2) Kronenbourg 1664, 5%, lager (KB) and 3) Elephant, 7.2% strong lager (EF), and one red wine (RW): Cabernet Sauvignon, Camenere and Shiraz, 2011, 13.5%, Palo Alto, Maule Valley, Chile, and ethanol (99%, Kemetyl, Køge, Denmark). All experiments were carried out with a stock volume of 900 mL (40 mL stock concentrate + 860 mL water) plus 150 mL alcoholic beverage (beer, wine or water + ethanol). The stock-beverage mixture was brought to the boil in an EVA trio stainless steel pot (with two exceptions in series 3 and 4; see Table 1) with a lid on a stove using the highest power input for 4 min. The lid was kept on for all reductions until the stock reached the boiling point (time 0). The reduction was then carried out at a lower energy input without lid, except for series 5 where the lid was kept on during the reduction. Throughout the 30 min of reduction samples of approximately 60 mL were taken and frozen prior to analysis. The stock pot was weighed before and after sampling throughout the reduction in order to determine the remaining stock volume as a function of time. The stock volumes were calculated based on an approximate density of 1 g/mL. Temperature was monitored during the reductions using a kitchen thermometer. Each experiment was repeated 2 7 times as also shown in Table 1.

2.2. Ethanol determination

Ethanol determinations were carried out using headspace gas chromatography mass spectrometry (HS-GS-MS). Each sample was analysed in duplicate. Methanol was used as internal standard.

A standard curve was prepared daily prior to each run. The standard curve was prepared by spiking a non-reduced stock sample (without added alcoholic beverage) with known amounts of ethanol. Each vial contained 1 mL ethanol/water solution + 8 mL water + 1 mL stock.

Prior to analysis, the reduced stock samples were diluted with water to a volume corresponding to the volume before reduction, in order to obtain a comparable matrix. The GC vials contained 1 mL stock sample + 9 mL water. The ethanol concentrations presented in the results are the actual concentrations in the reduced stock samples and they are given as a volume percentage (alcohol by volume).

Headspace gas chromatographic analyses were carried out on a Trace GC 2000 Ultra gas chromatograph with a split/splitless injection port coupled to a DSQ quadrupole mass spectrometer (Thermo, Waltham, MA). Head-space sampling was carried out using a CTC CombiPAL sampler (CTC Analytics AG, Zwingen, Switzerland).

Headspace sampling was performed after incubation at 60 °C for 25 min. A 250-μL aliquot of the headspace was sampled using a 2.5-mL syringe thermostated at 90 °C. Samples were injected in splitless mode (3 min), and injection port temperature was 250 °C.

Separation of compounds (ethanol and methanol) was done using a CP-WAX 52 capillary column (50 m × 0.32 mm i.d, 0.45 μm film thickness; Agilent, Santa Clara, CA). Helium with a constant flow of 1 mL/min was used as a carrier gas. After injection the column was kept at 40 °C for 10 min, and then raised at 30 °C/min to 240 °C. The temperature of the transfer line connected to the mass spectrometer was set at 260 °C.

Table 1
Experimental design. The table shows details of all stock reductions, divided into six experimental series. The parameters that were varied were the temperature of the stock during reduction (T), pot diameter (d), pot height (h), lid on or off (+/−) during reduction, the content and corresponding ethanol concentration of the 150 ml 'alcoholic beverage' added to the stock. The table furthermore shows the ID of the stock reduction experiments in each series and the number of replicates for each reduction experiment (n). Replicates are denoted with a letter **a g**.

Exp. series	T (°C)	d (cm)	h (cm)	Lid	150 ml alc. bev./c EtOH (v/v %)[a]	ID	n
1. Base	100	20	12	–	Brown Ale/6.0	Base	8 (a-h)
2. Temperature	*59*	20	12	–	Brown Ale/6.0	T59	2 (a,b)
	65					T65	2 (a,b)
	84					T84	4 (a-d)
3. Pot diameter	100	*16*	12	–	Brown Ale/6.0	d16	4 (a-d)
		30[b]		–		d30	4 (a-d)
4. Pot height	100	20	*7*[c]	–	Brown Ale/6.0	h7	2 (a,b)
			17			h17	2 (a,b)
5. Lid	100	20	12	+	Brown Ale/6.0	Lid	4 (a-d)
6. Alcoholic beverage	100	20	12	–	*Kronenbourg/5.0*	KB:5	2 (a,b)
					Elephant/7.2	EF:7.2	2 (a,b)
					Red wine/13.5	RW:13.5	2 (a,b)
					Brown Ale + Ethanol/7.9	BA+Et:7.9	2 (a,b)
					Brown Ale + Ethanol/9.6	BA+Et:9.6	2 (a,b)
					Water + Ethanol/4.0	W+Et:4	2 (a,b)
					Water + Ethanol/6.0	W+Et:6	2 (a,b)
					Water + Ethanol/8.0	W+Et:8	2 (a,b)

[a] Concentrations are based on concentration values specified on the bottle.
[b] Stainless steel pot (IKEA).
[c] Aluminium saute pan with ceramic coating (Beka Chef-Eco logic).

Detection was performed in electron-impact (EI) ionization mode with electron energy of 70 eV. Quantifications were performed in full-scan mode, mass range m/z 15 300, with a scan rate of 1.69 scans/s. Total ion chromatogram (ethanol) and m/z 32 (methanol) were used for quantifications.

Limit of detection (LOD) and limit of quantification (LOQ) were determined based on the signal-to-noise approach; i.e. SN = 3:1 for LOD and SN = 10:1 for LOQ.

2.3. Statistics

Statistics, including data fitting, was performed in Origin Pro 2015.

3. Theoretical model describing the loss of volatiles from a boiling liquid

Theories of elevation/depression of boiling points and fractionation by distillation are traditionally based on equilibrium thermodynamic theory (i.e. expressions for the chemical potentials of components in mixtures). Such theories work in general well, meaning that even though the systems are transformed by boiling, systems are transformed through equilibrium states and not influenced by non-equilibrium transport coefficients, such as diffusion coefficients. It should be pointed out that studying the loss of volatile components from a boiling liquid (i.e. loss of ethanol from a boiling stock) is basically the reverse way of studying distillation, where emphasis is on condensing vapours and collecting fractions with enhanced volatile concentrations.

Here we derive a simple theory for loss of a diluted volatile component from an evaporating solvent. For such a dilute component, the partial pressure (volatility) of the component is given by Henry's law,

$$C_i = K_{H,i} p_i,$$

where $K_{H,i}$ is the Henry's law constant for the specific combination of component 'i' and solvent, C_i is the molar concentration of the component 'i' in the solvent and p_i is the partial pressure of the component 'i'.

For the solvent (in most cases water) the vapour pressure in equilibrium with the dilute solution, denoted p_w, is very close to that of the pure solvent. Since we assume evaporation through equilibrium conditions, the rate of evaporation of water and the component 'i' can be assumed to be proportional to the partial pressures of the two components. Assuming vapours of the solvent and the volatile component to be ideal gases, the change of molar quantities, dn of the two components, "i" and "w" are linked through the relationship,

$$dn_i = \frac{C_i}{K_{H,i} p_w} dn_w.$$

Introducing the molecular volume of the solvent, v_w, gives a link between change in the molar amount of the volatile and the solvent volume, V

$$dn_i = \frac{C_i}{K_{H,i} p_w v_w} dV.$$

Integration and using the fact that $C_i = n_i/V$ gives,

$$C_i = C_{i,0} \left(\frac{V}{V_0}\right)^{\beta i}, \tag{1}$$

where the exponent is given by

$$\beta_i = \frac{1}{K_{H,i} p_w v_w} - 1. \tag{2}$$

When the component 'i' is much less volatile than the solvent, the term $K_{H,i} p_w$ approaches infinity and β_i approaches 1. In this limit, the concentration of component is inversely proportional with the volume as one would expect for complete non-volatiles. For volatile components, the term $K_{H,i} p_w$ will be small and β_i will be larger than 1, meaning that the concentration will diminish as the volume of the solvent decrease. The theory predicts that there is no specific effect of time or physical parameters of the set-up such as pot diameter or height. The exponent β_i will be a function of temperature as both $K_{H,i}$ and p_w depend on the temperature.

The system of water and ethanol is well studied with respect to Henry's law constants of ethanol at low temperatures and the various studies are summarized in Warneck (2006). The Henry's law constant of ethanol in boiling water is however not readily available in literature and one must obtain this indirectly from boiling point measurements. Using standard thermodynamic considerations for dilute systems (assuming ideal dilution, linearization of log function, considering temperature dependency of chemical potentials of both water and component i, etc.) one obtains an expression for the boiling point of a solvent containing low concentration of a volatile component

$$T_B(b_i) = T_B(0) - \beta_i K_B b_i, \tag{3}$$

where K_B is the ebullioscopic constant (0.512 K kg/mol for water) and b_i is the molality of the solute. Again, for non-volatile components β_i is -1 and Eq. (3) reduces to the normal equation for boiling point elevation; see any textbook on physical chemistry, for example Atkin and dePaula (2006). For sufficiently volatile components, β_i is positive and the boiling point is lowered.

Using experimental data for boiling point, Eq. (3) can be used to determine β_i as well as the Henry's law constant. Using linear regression on the data for ethanol in water (William, Noyes, & Warfel, 1901) the value of $\beta_i K_B$ is determined to be 4.35 K kg/mol and thus the exponent β_i to be 8.5 for ethanol in boiling water. In the interval between 0 and 60 °C data for Henry's law constants exist (Warneck, 2006) and the exponent β_i can be determined. Fig. 1 shows the temperature variation of β_i for ethanol in water, based on both data for Henrys law's constants and data for boiling point depression. The exponent shows a small temperature variation, approximately a factor of two, whereas the volatility of water (vapor pressure) and volatility of ethanol (Henrys law constant) show temperature variation over several orders of magnitude. However, the variation of the two volatility parameters almost cancels out, leaving β_i with very little temperature variation.

4. Experimental results

The decreasing stock volume as a function of time was recorded for all reduction experiments. The volume decreases continuously, due to evaporation, but because of sampling throughout the reduction process, the measured volume decrease has discontinuities. Since continuous volume data are desired, a corrected volume has been calculated, reflecting the evaporation only. The corrected volumes are calculated based on the amount of liquid that has evaporated in each step in the reduction and thus the corrected volumes express the decrease in volume by evaporation only. More detailed information on this and an example can be found in the Supplementary material. We have used the corrected volumes for the data analysis described below.

Ethanol was determined after various cooking times, t, throughout the reduction of 30 min. Examples of ethanol concentration as a function of time for seven stock reductions, representing four different experimental series (base, temperature, pot height, pot diameter) are shown in Fig. 2. Limit of quantification (LOD) was

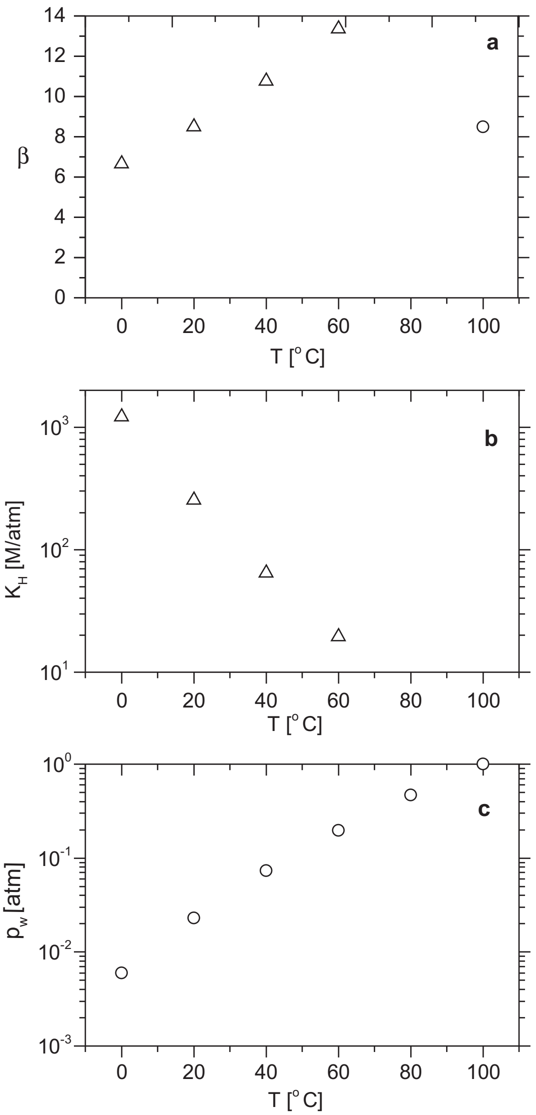

Fig. 1. Data related to the exponent β for ethanol in water. a) The exponent β based on data for Henry's law constants 0–60 °C (Δ) and based on boiling point data (○) from Warneck (2006). b) Data for Henry's laws constant. c) Data for vapour pressure of water. Both Henry's law constant and vapour pressure show a large variation over several orders of magnitude. This temperature dependence almost cancels out and the exponent β shows a very modest dependence on temperature.

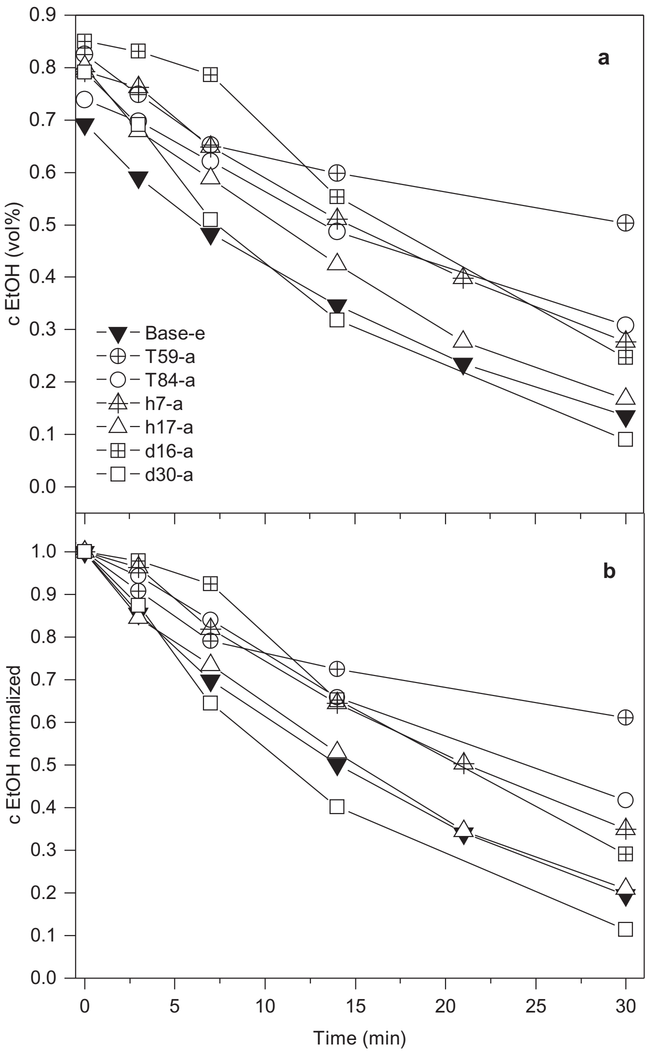

Fig. 2. Concentration of ethanol as a function of reduction time for seven stock reductions representing four reduction series, as described in Table 1. Reductions were carried out at 100 °C except from the 'Temperature series' that includes T59 and T89, which were prepared at 59 °C and 89 °C, respectively. a) The actual concentration as function of time. b) The normalized concentrations as a function of time.

≤0.03% and limit of quantification (LOQ) was ≤0.08% for all ethanol determinations.

It is seen in Fig. 2 that the time course of the ethanol concentration in the various experiments are very different even when the concentration is normalized with respect to the initial concentration. This variation indicates that cooking time by itself is not the natural variable for describing the loss of ethanol. It can also be observed (results not shown) that the rate and degree of decrease in stock volume caused by the evaporation of water varies in in the different experiments. The water evaporation depends on the temperature, settings of the stove and pot diameter. The decrease in volume should possibly be taken into account, in order to predict ethanol loss.

Inspired by the general theory describing a simple system of water and ethanol (or in general solvent and a volatile component), Eq. (1), the relation between remaining stock volume and ethanol concentration in the current experiments is studied. Fig. 3a shows the normalized ethanol concentration as a function of the fractional volume (based on corrected volumes) for the same seven stock reductions as shown in Fig. 2. It can be seen that the ethanol concentration decreases along with the decrease in remaining fractional volume. Noteworthy is that all reductions, despite the variation in reduction temperature and pot dimensions, show a very similar decline in ethanol concentration. Fig. 3a demonstrates how the individual curves almost collapse into a common master curve when depicted as function of fractional volume. There seem to be a unique relation between the fractional volume and the ethanol concentration, which is not affected by pot diameter, pot height or temperature. This suggests that the remaining fractional volume is the right variable to describe the ethanol concentration in a stock upon cooking, as also suggested by the theory for the simple system of water and ethanol.

More information can be obtained when studying the experimental series Alcoholic Beverage where the type of alcoholic beverage and corresponding alcohol percentage (4 13.5 vol%) were varied. The initial ethanol concentration of the stock mixture varied accordingly. When studying the normalized concentration values as a function of fractional volume (data not shown) of the

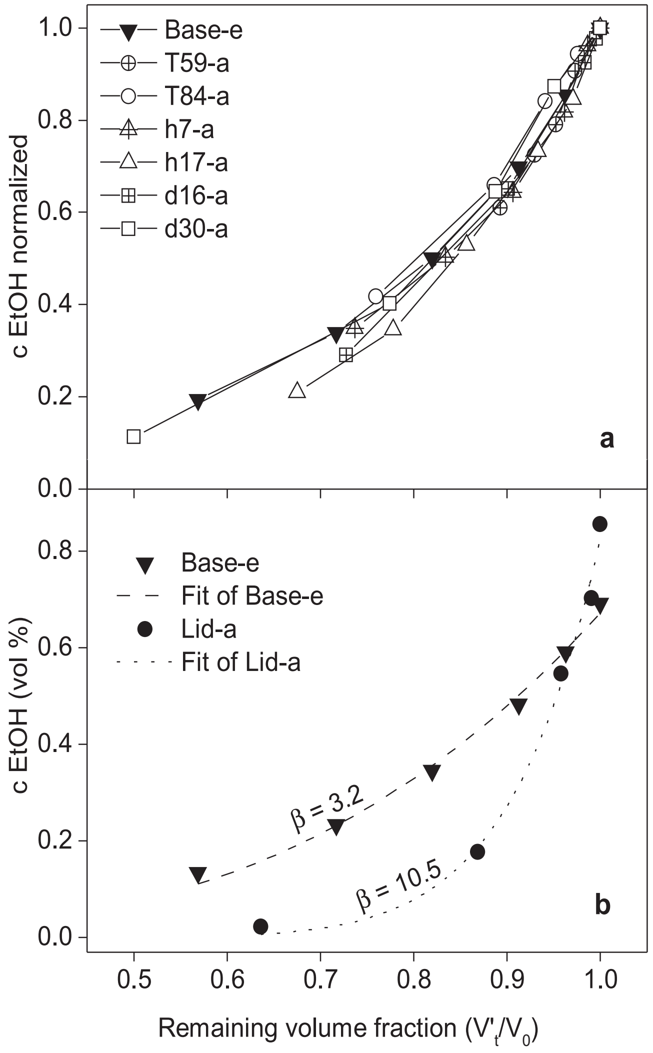

Fig. 3. Ethanol concentration as function of fractional volume (based on corrected volumes, V'_t). a) Normalized concentration values for seven experiments corresponding to those depicted in Fig. 2. b) Concentration values from two experiments; Base-e (no lid) and Lid-a (lid). The fitted values using Eq. (1) with C_0 and **β** as fitting parameters are shown as dotted lines.

experiments in series 6 (Alcoholic Beverages) a similar picture is seen as the one presented in Fig. 3a, since there apparently exists a common mathematical relationship between ethanol concentration and fractional volume despite differences in the initial concentration.

Only one cooking parameter, namely use of a lid, was able to change the picture completely as illustrated in Fig. 3b. In series 5 (Lid) the lid stayed on during the 30 min of reduction. It can be observed that in this case the ethanol concentration decreases noticeably more sharply when plotted as function of fractional volume. This is a seemingly counterintuitive result as one could naively imagine that the lid would retain the volatile component due to less evaporation. The observation indicates that the physicochemical conditions for evaporation are changed completely when using this set-up and this will be discussed further.

The theory for the simple system of only ethanol and water, Eq. (1), suggests that ethanol concentration follows a power law function of the fractional volume, characterized by a unique exponent β, which only slightly depends on temperature and does not depend on experimental details like pot dimensions or initial concentration. In order to investigate if the simple theory can describe reduction of the more complex stock systems Fig. 3b also shows fits of experimental data using Eq. (1), where β and C_0 are determined as free fitting parameters. It is seen that the experimental data from Base-e (no lid) are well described by Eq. (1) with a value of β determined to be 3.2. Likewise data for the Lid-a reduction (with lid) is also well described by the power law relation but for this steeper decrease in ethanol concentration, the value of β attains a higher value of 10.5. In order to test to which extent there exists a common mathematical relationship for ethanol loss, each of the 47 data sets was fitted using Eq. (1). The derived values of β and the quality of the fit, described by the adjusted *R*-square values, are shown in Fig. 4.

For most datasets, the adjusted *R*-square values were close to 1 which confirms a very good relation between the theoretical model and the measured concentrations during stock reductions. Additionally the predicted initial concentrations resulting from the fits corresponded well to the measured (data not shown).

With the Lid series being the only exception, the β-values do not change with changing cooking parameters but are found to be stable at a value close to 4. This confirms that there exists a unique relationship between ethanol concentration and fractional volume. The ethanol concentration during a reduction process is consequently only given by the initial concentration, the fractional volume and a common exponent β, which is close to 4.

As mentioned above and also illustrated in Fig. 4, one parameter changes the picture drastically. When the lid is kept on during the reduction, the β-values increase with a factor about two. This means that the ethanol concentration decreases more steeply when plotted as a function of the fractional volume when using a lid, as also illustrated in Fig. 3b. The use of lid is thus an exception from the common behaviour of the 47 experiments.

5. Discussion

A simple way to predict the amount of alcohol in a cooked dish is needed because many groups of people (children, doctors on duty, chauffeurs and pilots, religious etc.) avoid consumption of alcohol. The results of this study showed that when reducing meat stocks, the ethanol concentration at any given time is determined by the initial concentration and the remaining stock volume at the time. More precisely, the decrease in ethanol concentration follows the presented theoretical model which is based on a mixture of water and ethanol only.

The high correspondence between the theoretical model and the actual measured decrease in ethanol concentration during stock reduction implies that there is no direct relationship between the heating time and the remaining ethanol. The time factor is however partly determining the remaining volume and thus indirectly effects the ethanol concentration at any time.

The theoretical model further anticipated that parameters like stove settings and the corresponding temperature as well as pot dimensions should not directly influence the decline in ethanol concentration which is also confirmed in the stock experiments. These parameters can however likewise affect the decline in stock volume over time and thus indirectly affect the decline in ethanol concentration. Briefly, the faster the stock volume is reduced, the faster the ethanol concentration is diminished.

Fitting the experimental data in the current stock experiments without lid to the theoretical model resulted in a β-value of approximately 4. The β-value predicted by the model was 8.5 at boiling temperature, a factor two higher. Thus in practice the decrease in ethanol concentration was slower in the meat stocks than predicted by the β-values, based on available experimental values of Henry's law constants. The model stock used in this experiment is a more complex system, containing salts, fat and

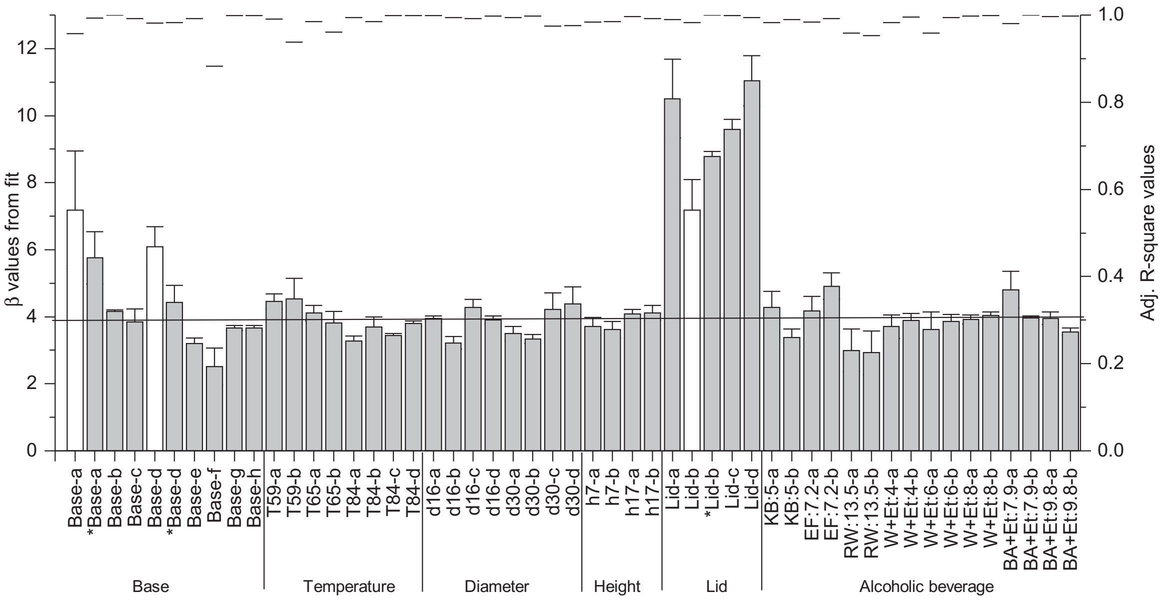

Fig. 4. Bars illustrate the exponent β, corresponding to Eq. (1), for each of the 47 experiments as determined by least squares fitting. Standard deviation on the obtained β-values is shown as pins. In three experiments, Base-a, Base-d and Lid-b, the fit was optimized (*) by leaving out a data point and both the original β-value (white bar) and the β-value from the optimized fit (grey bar) are shown. A horizontal line at β = 3.9 illustrates the mean value for the Base series (the mean value includes the optimized values for Base-a and Base-d only). The scatter plot shown in the upper part of the figure illustrates the adjusted *R*-squared values obtained by fitting.

proteins/peptides, as well as other important taste components like glutamate, etc. This allows other interactions than the one described by the Henry's law constant of ethanol in water alone. The lower value of β can be in interpreted as ethanol having a higher affinity to the complex stock media than to water and thus giving rise to a slower ethanol release. Ethanol could very likely interact more strongly with other constituents and partly partition into fat and thereby change the overall affinity and the observed β-value. The effect of other constituents on the course of ethanol decrease should be a subject of further investigations.

The practical outcome of these findings is that the ethanol concentration will decline more slowly than when cooking a simple mixture of water and ethanol, and it is consequently harder to 'cook off' all the ethanol in a stock based dish. If one wishes to diminish ethanol from the dish without sacrificing too much volume, one approach could be to cook the alcoholic beverage before mixing it into the dish, in line with what is done when preparing a wine reduction for various traditional French sauces. The two different approaches will however most likely give a different flavour to the end-product, as also shown by the studies with wine and stock by Snitkjær et al. (2011).

The use of a lid was able to dramatically enhance loss of ethanol when depicted as a function of fractional volume. The theoretical model presented was still valid in this case, but the β-values for experiments in the Lid series were approximately a factor two higher than seen for the additional experiments. The sharper decline in ethanol concentration when cooking with a lid indicates that the ratio between evaporating water and ethanol has changed in favour of ethanol by using a lid. We propose that the lid of the pot acts as a condenser creating liquid drops underneath the lid and some liquid will drip back into the pot and some liquid will evaporate. In that sense the lid acts as an extra plate in a distillation column and thereby enhanced separation of ethanol and water; more water will condense and ethanol will evaporate leading to an increased separation. One may imagine that the number of theoretical plates of the separation is dependent on the geometry of the combination of lid and pot, thus an optimized setup characterized by an even higher value of β may be devised, however only one combination of lid and pot was tested.

People who avoid alcohol will be concerned with the total amount of ethanol per serving, expressed in grams or alcohol units (one UK alcohol unit constitutes 8 grams of ethanol). The amount of ethanol is volume multiplied by concentration and Eq. (1) can be rewritten to describe the reduction in the total amount of ethanol. The amount of alcohol or volatile, m_i, then reads,

$$m_i = m_{i,0}\left(\frac{V}{V_0}\right)^{\beta i+1}, \tag{4}$$

where $m_{i,0}$ is the initial amount of volatile or ethanol. The amount of ethanol as a function of fractional volume thus decreases faster than the concentration, since the exponent is increased by 1. The practical outcome of the findings is that, by knowing the mathematical form, Eqs. (1) and (4) as well as the value of β, one can calculate the degree of volume reduction necessary to obtain a desired reduction in ethanol concentration or amount. For example, if the concentration is lowered by a factor of 0.1 and we assume a β-value of 4, then the volume should be reduced by a factor of 0.56. In order to reduce the amount of ethanol by 0.1, assuming the same β-value, the required volume reduction is 0.63. If less boiling is desired one can use a lid and obtain the same reduction in concentration and amount of ethanol by reducing volumes by only a factor 0.75 and 0.77, respectively, when assuming β to be 8.

As stated in the introduction, soups, stock and stews can contain other volatile components such as aroma components (e.g., from addition of wine or beer) and dissolved gases like oxygen. The ethanol molecule contains a hydroxyl group very well suited for hydrogen bond formation to water, making the molecule less volatile in a water-based liquid. In contrast many aroma components, like fruity esters from wine and beer addition, are more volatile than ethanol, having lower Henry's law constants, and will be characterized by higher values of β. At room temperature esters are typically at least a factor 50 more volatile than ethanol (Sander, 2015), and will thus boil off much faster, unless they interact with non-volatile components of the boiling food. Carbon dioxide from beer or champagne addition is characterized by a Henry's law constant of 0.034 M/atm (Sander, 2015), which is approximately 300 times lower than ethanol, leading to β values two orders of magnitude higher than ethanol. The sparkling effect will thus as expected be long gone by the time of consumption of the dish. Oxidation is of major concern for chemical stability of food components and oxidation is known to create off flavours. The rate of oxidation is increased at higher temperature and might thus be of concern for preparation of soups, stews and stocks. Luckily oxygen is even more volatile than carbon dioxide. Henry's law constant for oxygen at 100 °C has been reported to be $7.776 \cdot 10^{-4}$ M/atm by Tromans (1998). This low value of K_H corresponds to a high β-value of 68,410 according to Eq. (2), which demonstrates that we can expect the oxygen present in the boiling liquid food to be quickly expelled and extensive boiling should not lead to extensive oxidation caused by dissolved oxygen.

6. Conclusion

In conclusion, we have investigated the concentration of ethanol in boiling and heat-treated stocks as models for liquid food and demonstrated that the concentration of ethanol decreases as function of the remaining volume. This decrease can be described by a simple power law function with an exponent β. This exponent can be interpreted in terms of the interaction between ethanol and the liquid matrix as described by the Henry's law constant. The mathematical relationship can be used to calculate the degree of reduction by boiling needed to reduce ethanol concentration to a desired level in liquid foods, such as soups, stocks and stews. The practical outcome of the experiments is that there are three ways to control the ethanol concentration in a liquid food: 1) The initial concentration as defined by the recipe; 2) the remaining volume after cooking, as controlled by the parameters like cooking time, stove settings and pot dimensions; 3) whether to reduce with or without the lid.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foodchem.2017.03.034.

References

Atkin, P., & dePaula, J. (2006). Simple mixtures. In *Atkins' physical chemistry*, pp. 136–173). New York: Oxford University Press.

Augustin, J., Augustin, E., Cutrufelli, R. L., Hagen, S. R., & Teitzel, C. (1992). Alcohol in food preparation. *Journal of the American Dietetic Association, 92*(4), 486–488.

Hansen, C. E., Kwasniewski, M. T., & Sacks, G. L. (2012). Decoupling the effects of heating and flaming on chemical and sensory changes during flambé cooking. *International Journal of Gastronomy and Food Science, 1*(2), 90–95. http://dx.doi.org/10.1016/j.ijgfs.2013.04.001.

Helander, A., & Bergström, M. (2001). Kan man koka bort alkoholen ur glöggen? [Is it possible to boil away alcohol from the glogg-wine?]. *Lakartidningen, 98*(48), 5554.

Mateus, D., Ferreira, I. M. P. L. V. O., & Pinho, O. (2011). Headspace SPME–GC/MS evaluation of ethanol retention in cooked meals containing alcoholic drinks. *Food Chemistry, 126*(3), 1387–1392. http://dx.doi.org/10.1016/j.foodchem.2010.11.117.

Ryapushkina, J., Skovenborg, E., Astrup, A., Risbo, J., Bech, L. M., Jensen, M. G., & Snitkjær, P. (2016). Cooking with beer: How much alcohol is left? *Journal of gastronomy and Food Science*. http://dx.doi.org/10.1016/j.ijgfs.2016.09.001.

Sander, R. (2015). Compilation of henry's law constants (version 4.0) for water as solvent. *Atmospheric Chemistry and Physics, 15*(8), 4399–4981. http://dx.doi.org/10.5194/acp-15-4399-2015.

Snitkjær, P., Frøst, M. B., Skibsted, L. H., & Risbo, J. (2010). Flavour development during beef stock reduction. *Food Chemistry, 122*(3), 645–655. http://dx.doi.org/10.1016/j.foodchem.2010.03.025.

Snitkjær, P., Risbo, J., Skibsted, L. H., Ebeler, S., Heymann, H., Harmon, K., & Frøst, M. B. (2011). Beef stock reduction with red wine – effects of preparation method and wine characteristics. *Food Chemistry, 126*(1), 183–196. http://dx.doi.org/10.1016/j.foodchem.2010.10.096.

Tromans, D. (1998). Temperature and pressure dependent solubility of oxygen in water: A thermodynamic analysis. *Hydrometallurgy, 48*(3), 327–342. http://dx.doi.org/10.1016/S0304-386X(98)00007-3.

Warneck, P. (2006). A note on the temperature dependence of henry's law coefficients for methanol and ethanol. *Atmospheric Environment, 40*(37), 7146.

William, A., Noyes, A., & Warfel, R. R. (1901). The boiling-point curve for mixtures of ethyl alcohol and water. *Journal of the American Chemical Society, 23*(7), 463–468. http://dx.doi.org/10.1021/ja02033a004.