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Rotavap simulation and the estimation of boiling points

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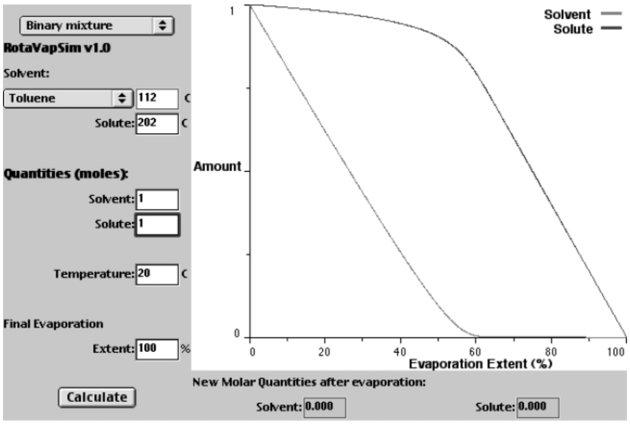
A Java applet that predicts solute losses during evaporation from a binary or ternary mixture has been developed which gives good agreement with experiment and can be used to estimate the boiling points of solutes, making use of information which is often collected and then discarded (http://www.ch.cam.ac.uk/magnus/rotavap/).

The rotary evaporator is a very common piece of equipment for organic chemists. Its use is routine to remove solvents, and in the same process some of the solute. It is desirable to have a high product yield and purity, so it would be useful to know how much of a solute is lost when the mixture is evaporated and how much solvent remains. To answer these questions a Java applet has been created (Fig. 1) which is available on the website: http://www.ch.cam.ac.uk/magnus/rotavap/

In order to use the applet, the user must supply boiling points and initial molar quantities for the two or three components. Common solvents can be selected from a list. The temperature of the mixture must also be selected. The ‘Calculate’ button is then clicked, and the applet plots a graph of the amount of solvent and solute remaining for various extents of evaporation. Ideally, all the solvent would be removed first, and only then the solute would start to evaporate. In practice, they both evaporate at the same time, particularly if their boiling points are not too dissimilar, or if the temperature of the rotavap water-bath is too high.

This can be quantified provided the vapour pressures of the solvent and solutes are known, and provided they behave as ideal liquids. The vapour pressures can be estimated using Trouton’s rule.[1] From the Clausius–Clapeyron equation[2] we obtain (eqn.(1)) for calculating the vapour pressure p at a temperature T of a liquid with a known boiling point T_b, where p^0 is atmospheric pressure, R is the gas constant and $\Delta S_{vap,Trouton}$ is Trouton’s constant (85 J K^{-1} mol^{-1} has been used). The equation relies on the molar change of volume upon vaporization being approximated to the molar volume of an ideal gas and on Trouton’s approximation that all liquids have about the same entropy of vaporisation. The rule gives good agreement for many liquids, with the least accurate results being obtained for water.[3]



Binary mixture
RotaVapSim v1.0
Solvent:
Toluene 112 C
Solute: 202 C
Quantities (moles):
Solvent: 1
Solute: 1
Temperature: 20 C
Final Evaporation
Extent: 100 %
New Molar Quantities after evaporation:
Solvent: 0.000 Solute: 0.000

Fig. 1 A screenshot from the applet showing its prediction for evaporation from a 1 : 1 mixture of acetophenone and toluene at 20 °C.

$$p = p^0 \exp\left[\frac{\Delta S_{vap,Trouton}}{R}\left(1-\frac{T_b}{T}\right)\right] \tag{1}$$

How the composition of a mixture changes during evaporation can be calculated using Raoult’s Law:[2] the partial vapour pressure of a component of a mixture is equal to the product of its mole fraction in the solution and its vapour pressure as a pure liquid. This means that the composition of the vapour above a mixture is, in general, different to the composition of the mixture. A rotavap removes the vapour, and so the composition of the liquid changes. Thus, if a small quantity δn of vapour in equilibrium with its liquid is removed from a mixture the change in molar quantity of a component A is given by eqn. (2), where x_a is the mole fraction of A in the liquid, p_{A*} is its vapour pressure as a pure liquid and p_{tot} is the total pressure ($p_{A*} + p_B*$ for a two component mixture).

$$\delta n_A = \frac{x_A p_A^*}{p_{tot}} \delta n \tag{2}$$

The applet uses eqn. (1) to calculate the vapour pressures of each component and then eqn. (2) to calculate the changes in molar quantities of each component (δn_A, δn_B *etc.*) after each removal δn. This differential equation is solved in the applet by numerical integration.

This analysis assumes that the solution behaves as an ideal mixture. Raoult’s law tends to hold for solutions of similar molecules. For many organic syntheses, solvents and solutes are both organic molecules, and so this may be expected to hold. At low concentrations, solutions tend to follow Henry’s law rather than Raoult’s law. Although much data is available for Henry’s law,[4,5] dilute solutions are only a small part of the range of mixtures modelled by the applet, and the transition from Raoult’s law to Henry’s law is hard to model. Therefore, these data have not been taken into account.

The applet does not need a measurement of the pressure used in the rotavap. This is because the pressure affects the rate of evaporation, but should not affect the change of composition that occurs whilst evaporation happens. If the solution boils, some material may splash over, and the composition may not follow the calculation. Provided this does not happen, the composition should change following the analysis above. As a result, a value for the pressure is not needed in order to calculate the concentration changes. In addition, it is possible to enter a temperature that is higher than the atmospheric boiling point of a component, as the applet will assume that the mixture does not boil, and so, presumably, the pressure used is higher than atmospheric pressure.

The applet calculates how much solute is lost as the solvent evaporates. For example, the applet calculates that if a 1 : 1 mixture of toluene and acetophenone is evaporated until half the material has gone, 8% of the acetophenone will have been lost at 0 °C, and 11% at 40 °C. If evaporation is continued until the acetophenone is 99% pure, there will be 85% of it left at 0 °C and only 77% at 40 °C.

In order to test the applet and the assumptions in the equations it uses, three experiments were carried out. The first and second involved evaporation from mixtures of acetophenone (boiling

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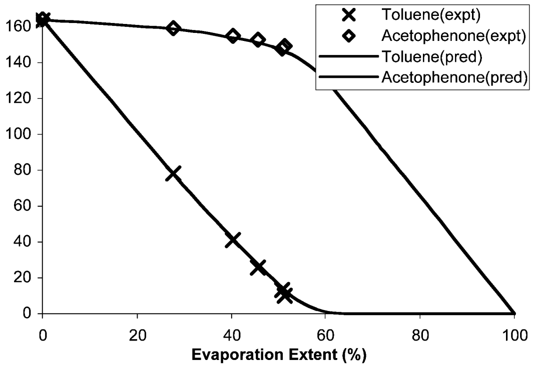

Fig. 2 A comparison between experiment and the applet's predictions for a mixture of 1 : 1 acetophenone and toluene at 25 °C.

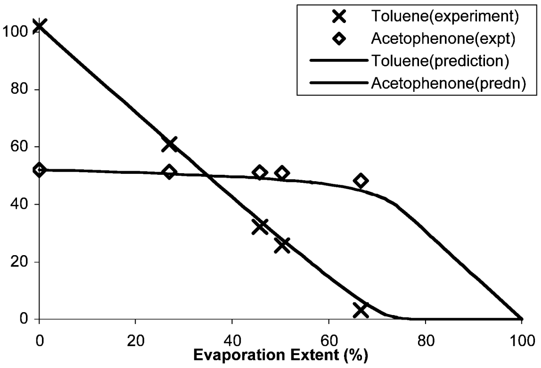

Fig. 3 A comparison between experiment and the applet's predictions for a mixture of 1 : 2 acetophenone and toluene at 40 °C.

point 202 °C) and toluene (boiling point 112 °C), starting with a 1 : 1 ratio (Fig. 2) and a 1 : 2 ratio (Fig. 3). The third experiment used a 2 : 1 mixture of dichloromethane (boiling point 40 °C) and toluene (Fig. 4). At various points throughout the evaporation, the mass of the solution was recorded and an NMR sample taken. This procedure allowed the molar quantities of both components to be calculated at each sample point, giving a way to compare the experimental data with the applet's calculations and this is illustrated in the figures. In all cases, the applet's calculations matches closely the experimental results.

We conclude that the applet agrees well with experiment in the cases of the binary mixtures tested.

If ratios of solvent and solute are available at two different points in the evaporation process, the applet's function can be reversed to calculate the boiling point of one component from the boiling point of the other and the changes in concentration as the evaporation proceeds. The applet has the facility to perform these reverse calculations. If the solute has a very high boiling point, then the best that can be expected is a lower bound on the boiling point. If, however, the boiling point is not so different from the solvent, higher accuracy might be expected. This requires experimental data which is often observed, but rarely gathered or reported – the changes in the size of solvent peaks as a compound is left under vacuum and the changes in the total mass.

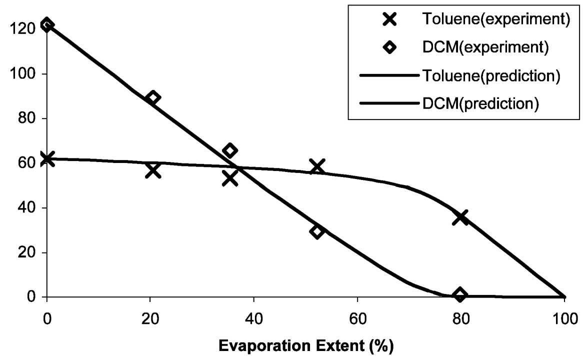

Fig. 4 A comparison between experiment and prediction from the applet for a 1 : 2 mixture of toluene and dichloromethane at 20 °C.

We used the experimental data again to estimate the boiling point of each of the components. For the experiment illustrated in Fig. 2, the results for toluene were used to estimate the boiling point of acetophenone, and *vice versa*, using the initial ratio and comparing it with each of the other measurements in turn. The results were an average of 206 °C for the boiling point of acetophenone, and 108 °C for toluene, comparing well with the literature values of 202 °C and 112 °C respectively. The standard deviation of the estimates was 2.2 °C for acetophenone and 2.6 °C for toluene.

This close correspondence was not repeated for the other two experiments. The second gave average values of 238 °C and 76 °C with standard deviations of 13 °C in both cases. The third gave average results of 170 °C and 54 °C, with standard deviations of 25 °C in both cases. Although these results are less closely correlated with the experimental results, they give useful guidance as to the approximate likely boiling points of the components of the mixture. The best results are from the experiment which had the largest difference between the rotavap temperature and the boiling points of the solvent and substrate.

If papers recorded the substrate/solvent ratio and total weight of material whilst the sample was being prepared, these data could be interpreted using this applet. This primary data is not usually recorded. However, it could be made accessible, and it may become important. Saving this primary information, which is often collected and then discarded, would add to the value of chemical papers. As it becomes possible to store more information in association with published articles, this sort of primary data may become more useful.[6] An estimate of the boiling range of a compound could be useful in preventing products being lost due to their boiling points being unexpectedly low. If the results show that the solution does not follow the course predicted by the applet, this indicates that the solution is behaving in a non-ideal manner, and may give an idea of the non-bonded interactions between solvent and solute.

The analysis assumes that the mixture is ideal, and this is not the case for all systems. For example, chloroform and acetone form an azeotropic mixture with a 2 : 1 molar ratio. In this case, the deviation from ideal behaviour leads to a mean absolute deviation from ideal behaviour in eqn. (2) of only 5%, and a maximum error of 12%, based on von Zawidzki's data.[7] Their boiling points are rather similar, however, and so the applet suggests that they should not be easily separated.

In conclusion, an applet is presented which models the changes in concentrations of solvent and substrate as solvent is removed. This could be useful both to provide help in deciding how much solvent it is possible to remove without losing an unacceptable amount of substrate, and also may give an indication of the approximate boiling point of the substrate.

We thank Professor Paul A. Bartlett for highlighting this problem.

Notes and references

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