Application of modified Raoult's law in a vacuum fermentation process

【Associated Sections in Selected Textbooks】

- Introduction to Chemical Engineering Thermodynamics [1] Sec. 10.5

【Module Learning Objectives】

- VLE calculation using modified Raoult's law.

【Problem】

Since typical fermentation broth contains low levels of ethanol, much of the energy consumption for commercial ethanol production is for distillation. Significant energy savings can thus be achieved if ethanol-rich fermentation broth is used. However, the growth and production ability of cells are inhibited by high ethanol and/or sugar concentration [2]. To prevent product inhibition, ethanol product must be removed from the fermentation broth as soon as it is formed. Simultaneous removal of ethanol stimulates the growth of yeast cells; thus, more sugars can be fermented and higher ethanol productivity was achieved as a result [2]. One way to achieve this is through vacuum fermentation. One particular design is shown in the following figure [3].

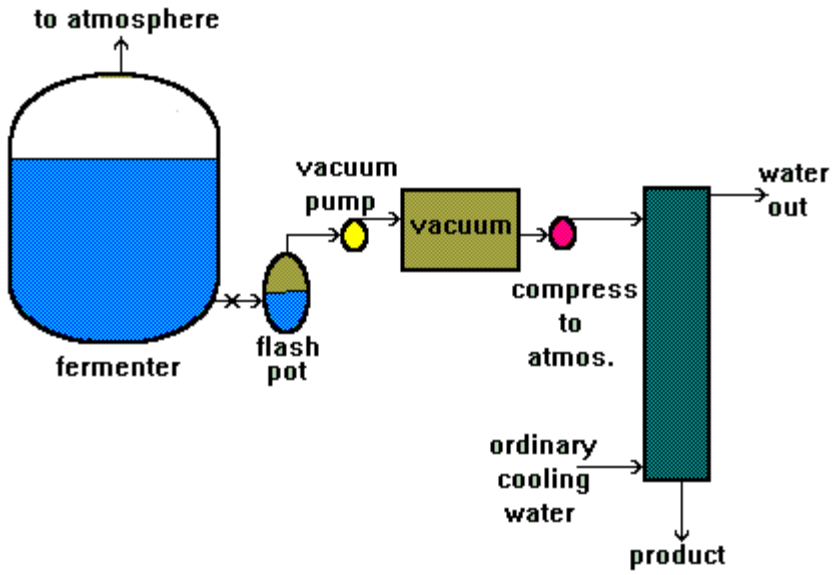

Figure 1. Schematic diagram of vacuum fermentation [3]

The fermentation broth is circulated through the flash pot for vaporization of the ethanol. The vacuum is adjusted to the vapor pressure of the alcohol-water solution at the fermentation temperature (30 to 40 ^{o}C).

Assume the ethanol-water solution in the flash pot reaches equilibrium and the modified Raoult's law applies. The following equations provide a reasonable correlation for the activity coefficients:

$$ln\gamma_1 = Ax_2^2 \quad ln\gamma_2 = Ax_1^2 \quad \text{where } A = 2.65 - 0.00575T(K)$$

a) If the fermentation broth at 35°C contains 0.1 mole fraction of ethanol, what would be the pressure in the flash pot and what is the mole fraction of ethanol in the vapor phase?
b) If we want to achieve 0.5 mole fraction of ethanol in vapor phase at 35°C, what would be the ethanol mole fraction from the fermentation broth? And what would be the pressure in the flash pot?
c) If the fermentation broth contains 0.1 mole fraction of ethanol and we want to maintain the vapor pressure in the flash pot at 5 kPa, what would be the operation temperature of the flash pot? And what would be the mole fraction of ethanol in the vapor phase?
d) If we want to maintain the vapor pressure in the flash pot at 5 kPa, at the same time achieve 0.4 mole fraction of ethanol in the vapor phase, what would be the ethanol mole fraction from the fermentation broth? What would be the operation temperature of the flash pot?
e) Show whether or not the system exhibits an azeotrope at 25°C. If there is an azeotrope, what are the azeotropic pressure and the azeotropic compositions for t=25°C?

Bibliography

[1] J. Smith, H. Van Ness and M. Abbott, Introduction to Chemical Engineering Thermodynamics, 7th Ed. ed., New York: McGraw Hill, 2005.

[2] V. D. Nguyen, J. Auresenia, H. Kosuge, R. R. Tan and Y. Brondial, "Vacuum fermentation integrated with separation process for ethanol production," *Biochemical Engineering Journal*, vol. 55, pp. 208 - 214, 2011.

[3] W. Wan, "Product removal during fermentation," [Online]. Available: http://www.rpi.edu/dept/chem-eng/Biotech-Environ/FERMENT/vacferm.htm.