Introduction

In this experiment, you will use thin-film evaporator (TFE) to separate a mixture of water and ethylene glycol (EG). In a TFE a mixture of two fluids runs down a heated inner wall of a cylindrical vessel as a thin liquid film. The vessel is heated to the boiling temperature of the more volatile component of the mixture (in this case, water). This component is then evaporated and leaves the vessel as the top flow. The vapor is transferred to a cooler where it is condensed. The less volatile component leaves the system as the bottom flow and is cooled using a heat exchanger. The rate of evaporation is enhanced by creating thin films with large surface-to-volume ratio. In order to ensure the thin film flow, a wiper is continuously rotating inside the vessel (see Figure 1).

To further enhance performance of the TFE, the pressure inside its chamber is reduced, which in turn reduces boiling temperature of the mixture. The system in the Unit Operations Lab uses a steam injector to reduce pressure in the TFE chamber. The injector contains a converging-diverging pipe. Reduction in the pipe diameter leads to an increase of the steam velocity which (according to the Bernoulli law) creates a low pressure zone.

Objective

The main objective of this experiment is a systematic investigation of effects of various parameters on the efficiency of the separation. Control parameters in this experiment are the feed flow rate $F$ and the pressure in the TFE chamber. In addition, you can vary the feed composition $x_F$. Effect of these parameters on the compositions and flow rates of the top and bottom streams should be investigated both theoretically and experimentally.

Note that it takes long time for this system to reach a steady state. Therefore, you should perform the theoretical calculations prior to the experiments to select conditions under which you can expect a measurable separation.
Theory

The following theory assumes that the TFE is operated at a steady-state. Note that in practice it may take a long time for the system to reach a steady-state. Therefore, it will be necessary to monitor the flow rates and concentrations of the top and bottom products as a function of time (see Operating Instructions).

The thin film flow is schematically shown in Fig. 2. Due to evaporation of water, the liquid flow rate decreases as liquid flows down the wall. Dependence of the flow rate on the position can be obtained from the mass balance and phase equilibrium conditions.

![Figure 2. Schematics of the thin film flow down the vessel wall. Film thickness decreases downstream due to evaporation.](image)

\[ F = \text{molar flow rate of feed} \]
\[ L = \text{molar flow rate of the bottom product} \]
\[ V = \text{molar flow rate of the top product} \]
\[ q(z) = \text{molar flow rate of the liquid at a given position } z \]
\[ x_F = \text{molar fraction of water in the feed} \]
\[ x_B = \text{molar fraction of water in the bottom product} \]
\[ y = \text{molar fraction of water in the vapor} \]
Consider a differential element between $z$ and $z+dz$. Due to evaporation, liquid flow rate $q(z)$ is not constant and we can write

$$q(z + dz) = q(z) + dq(z), \quad dq(z) < 0$$  \hspace{1cm} (1)

Molar rate of evaporation of water out of this differential element is

$$(\text{total amount of evaporated fluid}) \cdot (\text{water fraction in vapor}) = dq(z) \cdot y(z)$$  \hspace{1cm} (2)

This should be equal to

$$(\text{rate of loss of water from the liquid phase}) = d[q(z) \cdot x(z)]$$  \hspace{1cm} (3)

Equating right-hand sides of equations (2) and (3), we obtain:

$$y \ dq = x \ dq + q \ dx$$  \hspace{1cm} (4)

Rearranging the terms, we obtain:

$$\frac{dq}{q} = \frac{dx}{y-x}$$  \hspace{1cm} (5)

Now, integrate from the feed inlet ($z = 0$) to the bottom outlet ($z = H$):
\[
\ln \left[ \frac{q(H)}{q(0)} \right] = \int_{x(0)}^{x(H)} \frac{dx}{y - x}
\]  

(6)

Since \( q(0) = F \), \( q(H) = L \), \( x(0) = x_F \), and \( x(H) = x_B \), we obtain:

\[
\ln \left[ \frac{L}{F} \right] = \int_{x_F}^{x_B} \frac{dx}{y - x}
\]  

(7)

Assume vapor-liquid equilibrium in each differential element. According to the Gibbs phase rule, a two-phase equilibrium of a two-phase mixture has two degrees of freedom, e.g. pressure \( p \) and the molar fraction \( x \) of the more volatile component. Therefore,

\[
y = y(x, p)
\]  

(8)

Pressure is the same throughout the evaporator chamber and a relationship between \( x \) and \( y \) at a specific pressure can be obtained from vapor-liquid equilibrium (VLE) data available, e.g., from UniSim. Alternatively, the VLE curves can be obtained using Raoult's law and the Antoine equation.

Eqs. (7) and (8) represent the mass balance and the VLE, respectively. In order to complete the model, we also need to consider the energy balance:

\[
F H_F + \dot{Q} = L H_L + V H_V
\]  

(9)

Here, \( H_k \) is the molar enthalpy of stream \( k \) (\( k = F, L, \) or \( V \)) and \( \dot{Q} \) is the rate of heat transfer from the heating fluid (steam) to the fluid inside the evaporator. The dominant contribution to \( \dot{Q} \) is the latent heat of condensation. Therefore, \( \dot{Q} \) can be estimated assuming that the heating fluid leaving the system is a saturated liquid.

We can use Eqs. (7)-(9) numerically using VBA/Excel or Matlab to predict the flow rates and the compositions of the products. These predictions should be compared with the experimental measurements. The flow rates of the top and bottom products can be determined experimentally from the weight of the products and the run time of the evaporator. The stream compositions can be determined by measuring the refractive index (RI) of corresponding samples (see Operating Instructions).
Notes

1. This theory is similar to the Raleigh theory for batch distillation. The main difference is that batch distillation is not a steady-state process and the Raleigh theory predicts the change of the mixture composition over time. In the thin film flow, we assume a steady state process and consider the change of the composition in space as we move downstream from the feed.

2. The Gibbs phase rule implies that the temperature should change if the liquid composition changes at constant pressure. Therefore, the film temperature should change as it flows down the wall. A typical phase equilibrium diagram for a two-component mixture is shown in Fig. 4. Clearly, the temperature should increase if the fraction of the more volatile component in the liquid phase decreases. Therefore, the temperature at the top of the TFE should be lower than that at the bottom.

3. Make sure to experimentally verify the energy and mass balances as well as the assumption that the heat transfer from steam is dominated by the latent heat of condensation.

Figure 4. Phase equilibrium diagram for a two-component mixture at a constant pressure