Performance of Appended Wire Mesh Packing in Sieve Tray Distillation Column of Ethanol-Water System

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Abstract

For the separation process in liquid-liquid mixture such as ethanol-water mixture, a sieve tray distillation column is an alternatif for affordable process and maintenance. However to date, this sieve tray system is still currently having a lower Murphee efficiency and smaller interfacial area, as compared to other tray system, that is, either a bubble cap or valve tray. Therefore it is of important to optimize the performance of sieve tray distillation by means of adding the wire mesh packing on that tray, as being the aim of the present study. This study is conducted by using a batch sieve tray distillation system, where the wire mesh packing is added on the third tray that is calculated from the top of the column, to avoid flooding inside the column. Here the resulting fermented molasses of containing a 10% volume of ethanol is used as a mixture distillation feed. The height of the wire mesh packing being studied is varied as 5 cm, 3 cm, and 2 cm. Our results showed that the Murphee efficiency obtained by the variation of the packing height of 5 cm, 3 cm, 2 cm and without packing were 73.5%, 66.27%, 56.86%, and 46.7% respectively, and were increased by subsequent level of the packing height. The corresponding hydrodynamic properties of this appended packing sieve tray distillation by means of the interfacial area were 11.88 cm^2/cm^3, 0.48 cm^2/cm^3, and 0.32 cm^2/cm^3, while its pressure drop measured from the water manometer height were 38.33 cm H$_2$O/m, 30 cm H$_2$O/m, 10 cm H$_2$O/m for the packing height of 5 cm, 3 cm, 2 cm height, respectively. The increasing of the performance of appended packing sieve tray distillation by means of the Murphee efficiency is explained by the increasing of the interfacial area for vapour-liquid than the tray itself. This preliminary study is expected to be a pioneer study of strategy to increase the performance of conventional sieve tray distillation that is known as a kind of affordable distillation process.

Keywords: sieve tray distillation, wire mesh packing, ethanol-water, Murphee efficiency

1. Introduction

Distillation is prime method that is commonly used in industrial separation process. In a distillation separation process, there are various types of trays that can be utilized, namely sieve tray, valve tray and bubble cap tray. Among these trays, sieve tray has received interest from both the scientific and industrial communities, due to its affordable in cost and simplicity in design (GÓrak, A., & Olujić, Ž., 2014). Although sieve tray is of significance, the rationale design in its tray efficiency is an ongoing challenge. This challenge is generally correlated to the small interfacial area and poor tray efficiency resulted from the contact of vapour-liquid (Zuiderweg, F. J., 1982). Much effort has been devoted to answer this challenge, including the design of small hole size in sieve tray in order to produce small bubbles with large interfacial area, thus could improve the vapor-liquid contact and increase tray efficiency (Bain, J., & Van Winkle, M., 1961; Smith, B. D., 1963). However, this effort still struggles to fully meet the feasibility in economic aspect.

In contrast to the above sieve tray distillation column, a packed distillation column has a larger interfacial area, higher efficiency, less pressure drop, and suitable for corrosive substances. But it is not suitable for low flow rates liquid. (Spagnolo, D. A., & Chuang, K. T., 1984) are the pioneer to reveal on the possibility of combining sieve tray column with packing. To be precise, they incorporated a knitted mesh packing with bed size of 25 mm on the trays for the production of Girdler-Sulfide heavy water at the operating pressure and temperature of 2.17 MPa and 32 °C, respectively, where they found increasing tray efficiency by 3-20%. In particular methanol-water separation process, (Salem, A., & Alsaygh, A. A., 1988) reported that the incorporation of 115 mm bed of stacked stainless steel packing on the trays increased the tray efficiency by 21%. Similar system of

methanol-water mixture was also subjected into a packed sieve tray distillation column, where a knitted mesh packing was being particularly used by Chen, G. X., et al. In their study, the Murphree tray efficiency was found to be increased, in the range of 40-50%. (Kachur, P. J., et. al. 2004), studied the structured packing tray as an alternative for dual flow tray. They found that the structured packing tray was able to provide 44% improvement in capacity compared to that from dual-flow sieve tray using high liquid density systems. It also had found that its efficiency is 100% greater than the dual-flow sieve tray. (Xu, Z. P., et al., 1996) predicted the tray efficiency in relation with the addition of mesh packing in their modeling study. Similar to that of reported experimental studies, they found that the addition of mesh packing on the tray significantly increased its tray efficiency. Here the addition of packing will lead to the increase in interfacial area and vapor-liquid contact time. However, this phenomenon must be validated by the experimental studies. To the best of our knowledge, the experimental studies on validating the factors of packing on the interfacial area in sieve-tray distillation column and its corresponding efficiency have not been reported yet. Therefore, it encourages us to conduct an experimental based study with the aim to comprehend the addition of wire mesh packing with various heights on the resulting tray efficiency, and to validate the proposed factors that are responsible for the mechanism, *i.e.* interfacial area.

2. Method

In the present study, a sieve tray distillation column is modified by adding the wire mesh by means of increasing the vapor-liquid contact area in sieve tray column, thus increasing tray efficiency is expected. Here the height of wire mesh packing is varied as 5 cm, 3 cm, 2 cm, while its void fraction and wide area are conditioned as 0.94 and 20.5 cm^2, respectively. The experiment was carried out in batch system at a standard temperature and pressure condition. Ethanol and water mixture containing 10% mass of ethanol is used as feed. The wire mesh packing of having that 0.94 void fraction is only applied on the 3rd tray to avoid weeping and flooding. The effects of the addition of wire mesh packing and its different in heights, on the resulting single tray efficiency or known as Murphee efficiency, will be the focus of this study. In a relation with Fig 1 of the schematic diagram of the experimental apparatus, the procedure is started with closing the valve and turn on the water condensor. By using batch system, E-101 is initially filled with the mixture until it reached 80% the tank volume, and then is turned on. In the control panel B-101, the boiler temperature is set up at 110°C and from the TC3 reading was expected in 76.8°C or less. This is expected to prevent water impurities in the distillate and liquid-vapour sampling. As the design sieve tray column has 2 columns, thus P-101 is needed to pump the liquid from bottom C-102 to top C-101. Until the first drop of distillate begins to form and constant, some samples are taken from GV-106 for measuring ethanol-water concentration using alcohol meter. Then, full closed GV-106 for total reflux ratio and P-102 is turned on. Apparently, y_n, y_{n+1} and x_n are required for calculating Murphee efficiency, and to do that, which some amount of sample is taken from V-102, V-103, and V-104.

Note of schematic of experimental apparatus:
C-101 : Distillation Column 1
C-102 : Distillation Column 2
V-101 : Receiver drum
V-102 : Vapor Sampling Vessel
V-103 : Liquid Sampling Vessel
V-104 : Vapor Sampling Vessel
E-101 : Boiler
E-102 : Condenser Distillate
P-101 : Liquid Pump to C-101
P-102 : Reflux Pump
B-101 : Control Panel
GV-101: Bottom Valve
GV-102: Drain Valve
GV-103: Vapor Sampling Valve
GV-104: Vapor Sampling Valve
GV-105: Liquid Sampling Valve
GV-106: Distillate Valve
Tc1   : Top Column 1 Termo-couple
Tc2   : Boiler Thermocouple
Tc3   : Top Column 2 Termo-couple
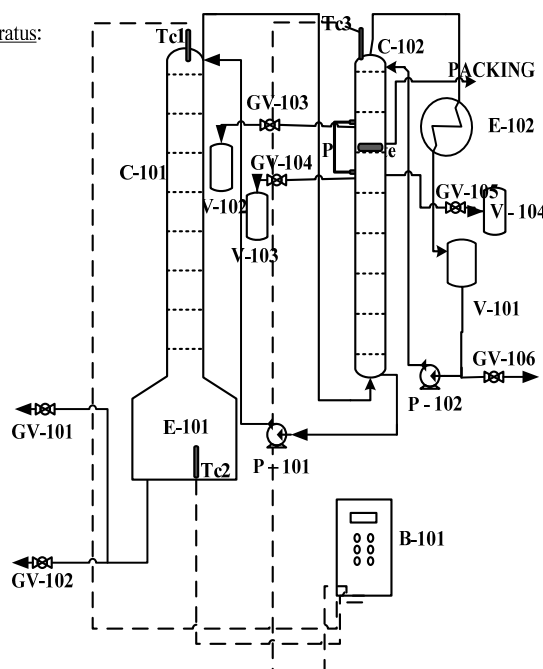*P*   *:* Pressure Indicator

Figure 1. Schematic diagram of packed sieve trays for distillation column

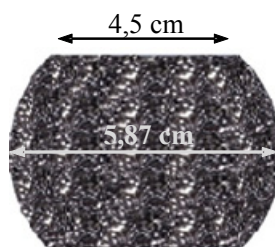Figure 2. Snapshot photos of a single sieve tray without packing

Figure 3. Wire mesh packing

Table 1. Detail dimensions of the columns and test

No.	Parameter Dimension	Detail Dimension
1	Column diameter	5.87 cm
2	*Tray* Spacing	30 cm
3	Hole diameter	2 mm
4	Column height	2.5 m
5	Number of tray	16
6	Tray type	Sieve *Tray*
7	Weir height	5 cm

Here the interfacial area of packing is calculated from 2 step consecutive equations, *i.e.* equation 1 and 2, as follows. First, specific surface area of packing is calculated by the relationship with the relative volatility, density of both vapor and liquid.

$$\alpha = a_p \left[\left(1 + 0.78 e^{0.00058 a_p} \right) \left(\frac{\rho_G}{\rho_L} \right)^{0.25} \right]^2 \qquad (1)$$

where α = relative volatility, $\rho_{G=}$ density vapor (kg/m^3), $\rho_{L=}$ density liquid (kg/m^3), and $a_{p=}$ specific surface area of packing (cm^2/cm^3). After obtaining the specific surface area of packing, look for the interfacial area obtained by the following equation (McCabe, W. L. *et al.*, 2001, Van Winkle, M., 1967):

$$a_W = a_p \left\{ 1 - \exp \left[-1,45 \cdot \text{Re}_L^{0.1} \cdot Fr_L^{-0.05} \cdot We_L^{0.2} \cdot \left(\frac{\sigma}{\sigma_C} \right)^{-0.75} \right] \right\} \qquad (2)$$

With Re$_L$, We$_L$, and Fr$_L$ are described as follows.

$$\text{Re}_L = \frac{G_L}{a_p \cdot \mu_L} \qquad (3)$$

$$We_L = \frac{G_L^{\,2}}{a_p \cdot \sigma \cdot \rho_L} \qquad (4)$$

$$Fr_L = \frac{a_p \cdot G_L^{\,2}}{g \cdot \rho_L^{\,2}} \tag{5}$$

where a_w = Wetted (interfacial) surface area of packing (m), Re_L = Reynolds number for liquid, Fr_L = Froude number for liquid, We_L= Weber number for liquid, G_L = Liquid mass flow (kg/h.m), S = Surface tension (N/m), μ_L = Viscosity of liquid (kg/m.s), a_p = Specific surface of packing (cm^2/cm^3), and g = Gravity acceleration.

Based on the data of interfacial area, the vapor velocity in each packing height can be the obtained. Several calculation steps must be carried out, first step is to calculate effective particle diameter by assuming that the shape factor of particular packing is 0.87 (based on shape factor of cylinder packing.

$$D_p = \frac{6}{\varphi_S a_v} \tag{6}$$

Second step is to substitute the obtained effective particle diameter, the viscosity and density of vapor, the measured pressure drop, the void fraction and height of the packing, into the Ergun equation, to obtain vapor velocity by trial method (Geankoplis, C. J., 1993).

$$\Delta p = \frac{150 \mu \upsilon' \Delta L}{D_p^{\,2}} \frac{\left(1 - \varepsilon^2\right)}{\varepsilon^3} + \frac{1.75 \rho \left(\upsilon'\right)^2 \Delta L}{D_p} \cdot \frac{1 - \varepsilon}{\varepsilon^3} \tag{7}$$

where a_v =Interfacial area (cm^2/cm^3), Φ_S = Shape factor, ΔP = Pressure drop (N/m^2), μ = Viscosity of vapor (kg/m.s), v' = Vapor velocity (m/s), ΔL = Packing height (m), ε = Void fraction

3. Results and Discussion

Figure 4 shows the effects of packing heights on their corresponding interfacial areas. As can be seen from this figure, the interfacial area were found to be 11.88 cm^2/cm^3, 0.48 cm^2/cm^3, and 0.32 cm^2/cm^3 for the packing height of 5 cm, 3 cm, 2 cm height, respectively. The increasing of interfacial area is affected by the increasing of packing height, with higher packing height tend to have better liquid-vapor contact. This can be explained by the fact that presence of mesh-packed tray would tend to generate uniform smaller bubbles compared to that of from sieve tray only, which is usually followed by an increase in interfacial area. (Chen, G. X., et al., 1992).
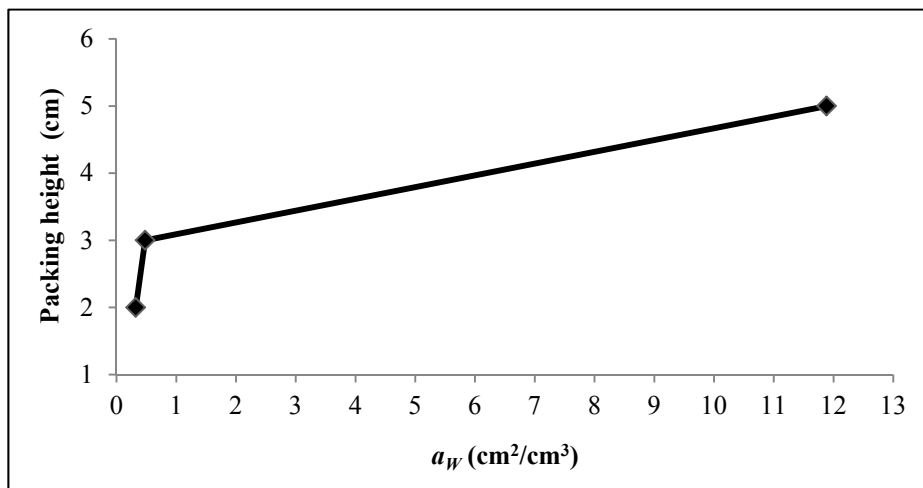

Figure 4. Interfacial area with different height

Figure 5 shows the effects of packing heights on their corresponding Murphee efficiencies. To obtain the Murphee efficiency itself, the samples from yn, yn+1 and xn must be taken. Here the yn is mole fraction of more volatile component from vapor stream above the tray while for that of yn+1 is from below the tray. The yn* is mole fraction of the vapour stream above the tray, which is in equilibrium with its liquid stream (Perry, R., et al., 1997). Using the ethanol-water equilibrium curve, the yn* is obtained from the data of xn, which is measured from the experiment. In detailed observation in this figure, the Murphee efficiency (EMV) is found to be increased by the increase in packing height. To be specific, EMV of 47 % is obtained from tray without packing; while the EMV of 74 % is obtained from tray with 5 cm packing height, which means there is an increase in

efficiency of 58 % from 47 %. EMV of 66 % is obtained from tray with 3 cm packing height, which means there is an increased efficiency of 42 % from 47 %. For the smallest packing with 2 cm height of having EMV of 57 %, it is found that an increased EMV of 22 % from 47 %. In general, overall Murphee efficiency increased in between 21-57 % compared to that of without packing. This increase in Murphee efficiency can be explained by the fact that the addition of packing enhances the contat between liquid-vapor, as explained in Figure 4. Also, the froth with smaller bubble size tends to have a higher surface tension (Spagnolo, D. A., et al., 1984).
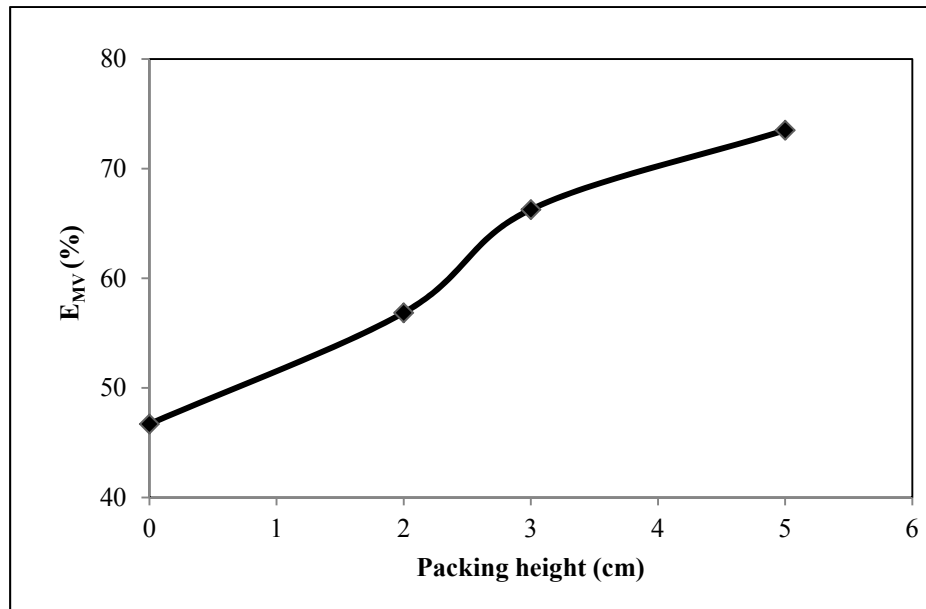

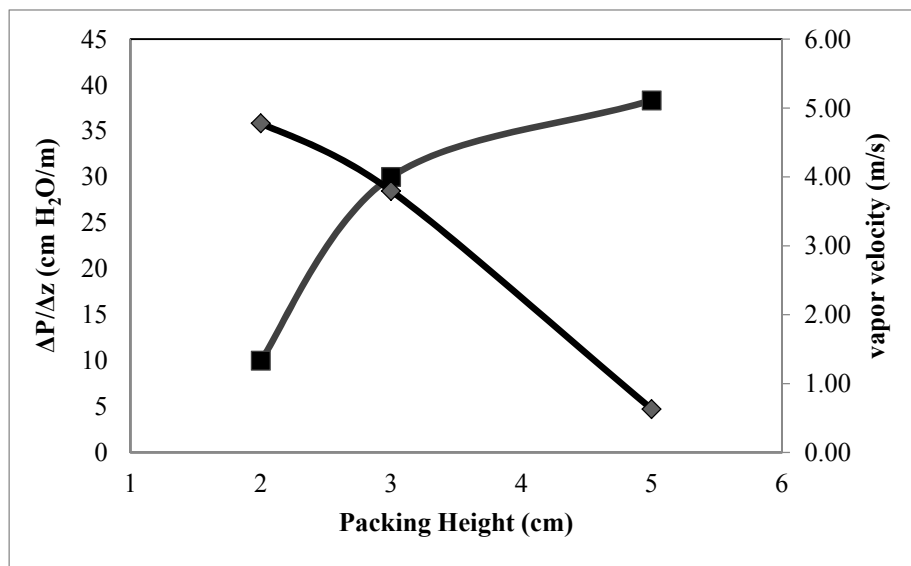Figure 5. EMV(%) result from different packing height (cm)

Figure 6. Measured $\Delta P/\Delta Z$ (cm H2O/m) and vapor velocity (m/s) from different packing height (cm)

From Figure.6 explained that pressure drop measured from the water manomater height were 38.33 cm H_2O/m, 30 cm H_2O/m, 10 cm H_2O/m for the packing height of 5 cm, 3 cm, 2 cm height, respectively. This indicates that the mass transfer effciency is very high in the packing zone because of the large interfacial area. Pressure drop increased along with the increasing interfacial area (Chen, G. X., et al., 1992).

Nevertheless, significant difference in pressure drop is shown for packing with 2 cm and 3 cm height, as explained before in Figure.4, where it can be correlated by the gradient in interfacial area. According to Chen, G. X., et al., the presence of mesh packing in sieve tray column showed a lower weeping and entrainment effects,

yet showed a higher froth and pressure drop effects. The effects of entrainment and weeping could be suppressed because of the presence of mesh packing could break up the vapor into smaller size and stabilize the bubbles, thus in effect the vapor could flow through to the next tray. If some liquid also brought by the vapor through the next tray, this would decrease the Murphee efficiency. Higher froth height would prevents the liquid to fall through the next below tray, and thus could lower the weeping effect.

Figure 6 also explained the correlation between packing height and vapor velocity. According to Ergun equation (Geankoplis, C. J., 1993) that is applicable in low, intermediate, and high Reynolds numbers, the vapor velocity were found to 0.63 m/s, 3.8 m/s, 4.76 m/s for the packing height of 5 cm, 3 cm, 2 cm height, respectively. This means the increase in packing height will result in decrease in vapor velocity. This finding is consistent with the previous discussion on interfacial area (see discussion on Figure 4). The increase in packing height will tend to improve the liquid-vapor contact, by making a uniform and stable small bubbles result. This will also result in increase in froth height and residence time, thus it gives an increase in pressure drop.

Acknowledgments

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