

HYDRODYNAMIC AND MASS TRANSFER STUDY IN PARASTILLATION COLUMNS

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Abstract. This paper investigates some aspects of the Parastillation process, which employs a unique distillation column. In a typical Parastillation column, the vapor stream is divided into two equal parts at the bottom of the column by a partition running the full height of the column. The whole falling liquid is contacted alternatively on a stage by stage basis with both parts of the vapor. Though the theoretical principles have been known for a few years, this process has not yet reached industrial scale due to the lack of experimental data. The experiments carried out used an ethanol-water system and a twelve stage Parastillation column with circular downcomers. The experiments were conducted to study the influence of the vapor stream flow rate and the effect of the reboiler initial ethanol concentration on the hydrodynamic conditions. The limiting operating conditions were defined for each case. The results indicated that vapor stream superficial velocity is an important parameter to be determined for tray stable operation. Murphree separation efficiencies for the process were calculated and discussed for a wide range of operating conditions. This efficiency appears to be strongly dependent on the system properties as well as on the liquid phase composition on the tray.

Keywords. Parastillation, Distillation Hydrodynamics, Murphree Efficiency

1. Introduction

Distillation is a process in which a liquid-vapor mixture of two or more substances is separated into streams of desired compositions, by the application and removal of heat. Distillation columns are designed to achieve this separation efficiently.

Distillation is the most common separation technique and consumes enormous amounts of energy, both in terms of cooling and heating requirements. It contributes to more than 50% of plant operating costs. The best way to reduce operating costs of existing units is to improve their efficiency. To achieve this, a thorough understanding of distillation principles and how distillation systems are designed is essential.

Several techniques have been proposed in the literature to decrease distillation energy consumption. One of these methods was proposed by Canfield (1984) and is based on the division of one of the phases into several parallel flows, which allegedly promotes a better separation. Parastillation is one instance of these configurations. In the Parastillation column, the vapor is divided into two equal parts at the bottom of the column by an axial partition running the full height of the column and the whole falling liquid stream is contacted alternatively on a stage by stage basis with both parts of the vapor. According to case II of Lewis (1936), an advantage of the Parastillation process over traditional distillation is that the liquid in a given vapor side of the column always flows in the same direction.

Canfield (1984) analyzed the Parastillation process under total reflux conditions, using non-rigorous computational simulation and his results were supported by experimental tests conducted in a six tray distillation column. Under these conditions, Canfield concluded that the Parastillation process is more advantageous than conventional distillation due to higher Murphree efficiencies.

Heucke (1987) analyzed the benefits of Parastillation of binary mixtures using McCabe Thiele diagrams.

Meszáros and Fonyo (1990) developed a computational program based on the Wang-Henke method to simulate Parastillation columns and analyzed the behavior of some ideal systems operating under partial reflux conditions. They observed that on conditions of partial reflux not always one observes greater Murphree efficiency values for the Parastillation process. According to them, to obtain the same separation, the number of stages of a Parastillation column should be 40% higher than for a conventional column. In spite of this, as in the Parastillation process the trays

are disposed on a different arrangement, a shorter column results. Finally, they concluded that the Parastillation process provides considerable energy saving.

Gouvea (1999) developed a computer program to simulate the column operation. This simulation used the rigorous MESH equations applied to a multicomponent Parastillation column. The non-linear algebraic equations system was solved using Nalptali-Sadholm method. He analyzed the behavior of ideal and non-ideal distilling systems. According to him, although the number of stages in a Parastillation column is 40% higher than in a conventional column, the results showed that due to geometry configuration, for the same spacing among the trays, the Parastillation column was 20 to 30% lower. Consequently, lower pressure drops are expected in this column. Another important observation was the decrease in the column diameter in a Parastillation process. The tray area obtained was about 33 to 44% smaller. It was also observed a 9% reduction in energy consumption. For the Parastillation column, Gouvea (1999) noted a cost reduction between 7 and 12%. Finally, Murphree tray efficiency for distillation and Parastillation process were calculated and discussed. Average values were either higher than or equal to the ones obtained for the conventional process.

In the present work, a laboratory scale apparatus was used to study the Parastillation column hydrodynamics. Depending on the local tray ethanol concentration, different regimes occurred on the tray, once fixed the liquid and vapor flow rates. Murphree efficiency values, considering flooding and weeping effects, were calculated and discussed for a wide range of operating conditions.

2. Experimental Equipment

The objective of this work was to study a Parastillation column with perforated trays and circular downcomers. A laboratory scale column of this type was constructed for collection of experimental data. The unit comprised the column, a condenser, a reboiler with electric heating and a control panel. The unit is sketched in Fig.(1).

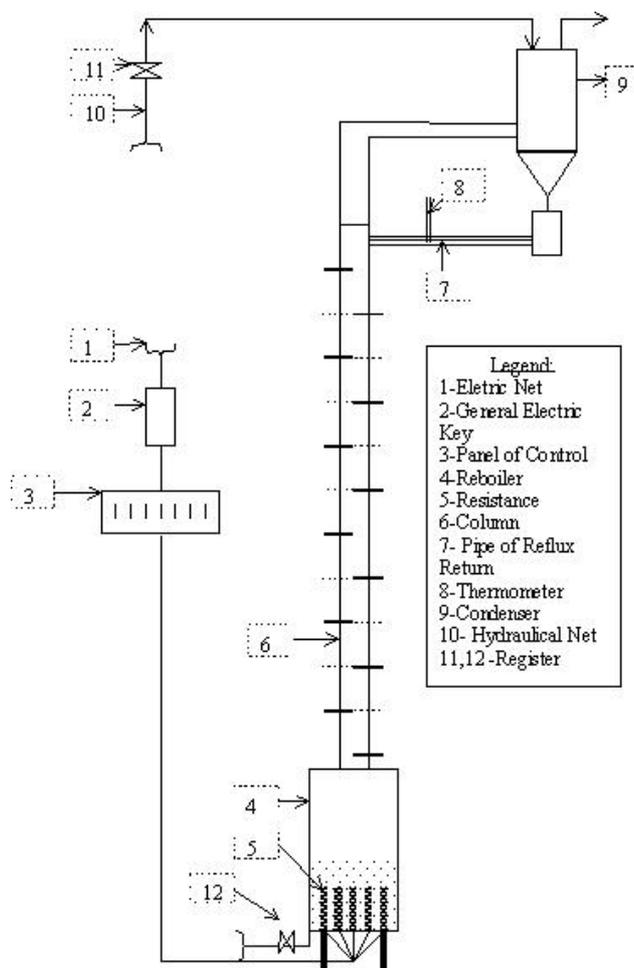


Figure 1. Schematic diagram of the experimental equipment.

The experimental work was carried out employing a column with twelve sieve trays. A rectangular brass plate was used to divide axially the full height of the column in half, which provided two parallel sides.

The trays were made of 0.21 cm brass sheets. The cylindrical sections among trays were made of Pyrex glass tube, with 10.0 cm of internal diameter and 15.0 cm of height, kept in place by support beams fastened between consecutive

trays; rubber gaskets were used between the glass tubes and trays. The upper section was, however, made of brass, in which a lateral pipe was welded to allow the return of the corresponding condensed liquid to the column.

Twenty two circular holes were sharply drilled on each half-circle tray following a triangular pitch. The holes were 2.0 mm diameter in all trays. Thus, each tray possessed a free draining area of 1.90%.

The circular downcomers, which promoted the passage of liquid from side to side of the column, were made of aluminum pipe with 0.96 cm of internal diameter and 1.30 cm of external diameter.

The column was insulated.

At the top of the column, above the last stage, there was a condenser 60.0 cm long and 15.0 cm diameter as shown in the Fig. (1). The conical part was 7.0 cm high and it possessed a 1.2 m² thermal exchange area. Water, the cooling fluid, condensed all vapor leaving the column.

The liquid mixture used in the process was feed to the reboiler, as shown in Fig.(1). The reboiler was made of stainless steel, with 56.0 cm of height and 22.0 cm of diameter. A set of electrical resistances was used to heat the liquid mixture contained in the reboiler.

A typical stage layout is seen in Fig.(2), which shows how the liquid flows helicoidally from one side to the other side of the column. Figure (3) compares the stage layouts between the Parastillation and a conventional distillation column.

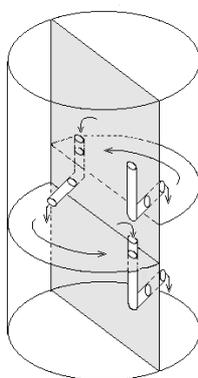


Figure 2. Parastillation column with a circular downcomer.

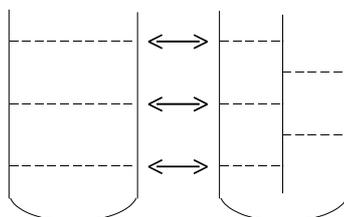


Figure 3. Comparative design of the space between trays of a conventional distillation column (left) and a Parastillation column (right).

3. Experimental Procedure

The column operation under total reflux is the condition in which all vapor is condensed and returned to the top of the column as reflux. All experiments were carried out under total reflux conditions. The column pressure was the local atmospheric pressure of 94.23 kPa.

The experiments were carried out using an ethanol-water system. This mixture, at 101.3 kPa, presents an azeotropic point at the ethanol molar fraction of 0.894 and boiling temperature of 351.3 K.

Several observations and measurements were made during steady state condition: dispersion type, dispersion height, condensed vapor flow and composition. Liquid samples were withdrawn at all trays. The type of the dispersion was observed visually and its height was measured with a millimeter scale placed externally on each stage section. In a few cases, in which the dispersion presented oscillations, the recovered dispersion height was an average value.

Liquid samples were collected at the downcomer exit with the aid of syringes through the rubber gaskets of each tray. The liquid phase composition was then determined by the refractive index method.

Experiments were conducted to study the influence of the vapor velocity and ethanol composition on the hydrodynamic conditions. The reboiler initial ethanol concentration was varied (2%, 3% and 4% molar). The limiting

operating conditions were determined for each case. Flooding and weeping were observed and represented respectively the upper and lower operating limits.

A computer program in Fortran language was developed to solve the mass and energy balances. The calculation provided the vapor and liquid flow rates, the vapor composition of each tray and the Murphree efficiency. The physical properties of the pure components were obtained based on experimental data presented by Vargaftik (1975). Vapor-liquid equilibrium data were predicted using Wilson method whose binary parameter were obtained from Gimehling et al. (1982).

4. Results and discussion

4.1. Hydrodynamics

The flow regime is defined by according to the vapor-liquid dispersion on each tray. Both the dispersion hydrodynamics and height may vary. The dispersion height depends on the vapor and the liquid flow rates, on the tray geometry and the chemical and physical properties of the phases. The form the dispersion arises affects the mass transfer. Therefore, an analysis of flow regimes is important.

Moreover, a tray operates satisfactorily within a certain range of vapor flow rate; out of these limits, the efficiency is reduced to unacceptable values. Above the upper limit, flooding occurs. Flooding is accumulation of liquid inside the column. This accumulation is generally caused by high vapor flow rates. A loss of separation is then inevitable.

The lower operating limit, named the weeping point, is defined as the vapor flow rate when liquid descending through the tray perforations becomes noticeable. Under weeping conditions, part of the liquid flows through the perforations instead of the downcomer. This flow short-circuits the primary contacting zone, causing a reduction of tray efficiency.

In this context, for each initial ethanol concentration in the reboiler, the influence of the reflux flow rate was analyzed for a wide range of values, from the minimum limit of operation (weeping) to the maximum limit of operation (flooding). Typical experimental results obtained on the Parastillation column are showed from Fig. (4) to Fig. (6). In these figures, stage 13 corresponds to the condenser.

The results of Fig. (4), (5) and (6) indicate that increases in reflux flow rates increase the dispersion heights in the upper trays, causing higher ethanol concentrations in these trays. Consequently, the bottom trays present low ethanol concentrations. For example, as shown in Fig. (6a), the high reflux of 8.9392×10^{-5} kgmol/s, caused high ethanol mole fraction from 10th tray, while for a lower reflux of 1.6115×10^{-5} kgmol/s, significant ethanol mole fraction were presented from the 3rd tray. With this, a decrease in the reflux allowed a higher distribution of ethanol along the column; accordingly a fall in the dispersion height occurred.

Regarding the influence of the initial ethanol concentration in the reboiler, it was observed that the increase of this initial concentration allowed a higher ethanol distribution along the column as a function of the reflux flow rate. Comparing Fig. (6) to Fig. (4), no significant changes on the ethanol distribution were observed for the initial concentration of 2%, while for the initial concentration of 4% the ethanol distribution was well evident.

The results from Fig. (4) to (6) clearly show that the ethanol concentration in the condenser was higher for smaller reflux flow rates, i.e., an increase in the reflux flow rate resulted in a reduction in the ethanol concentration in the condenser.

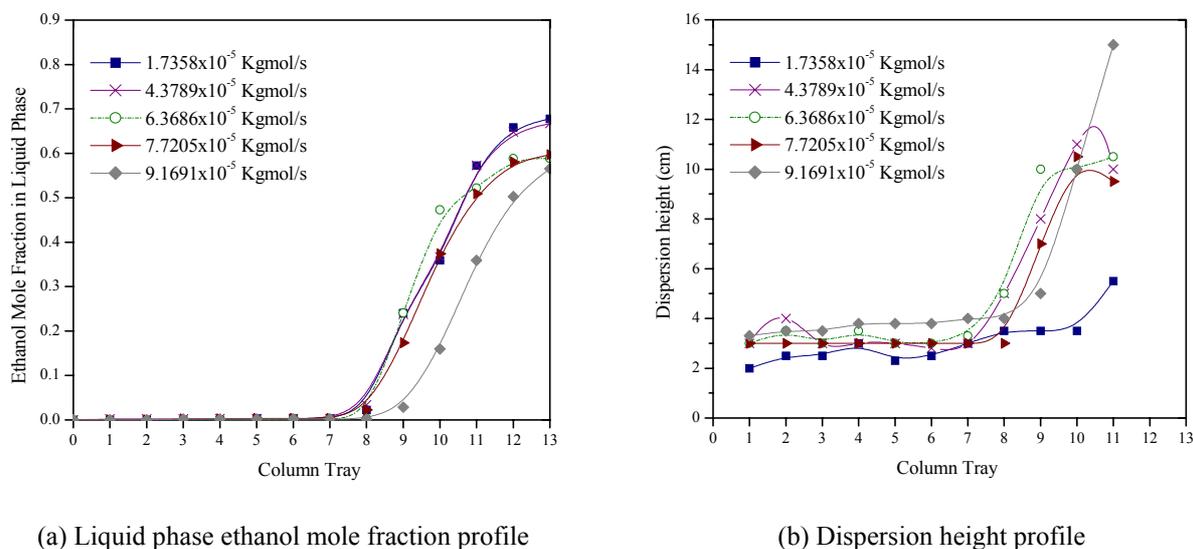
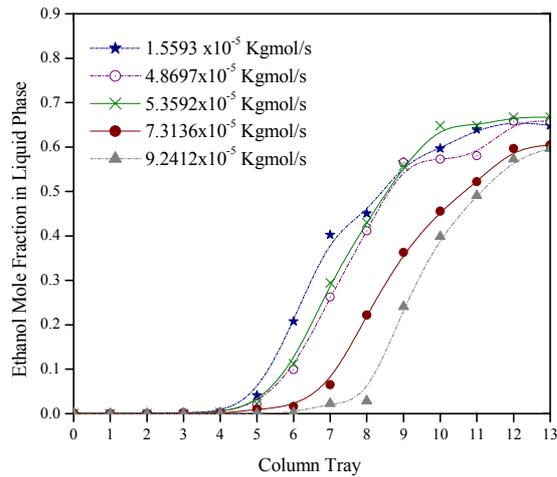
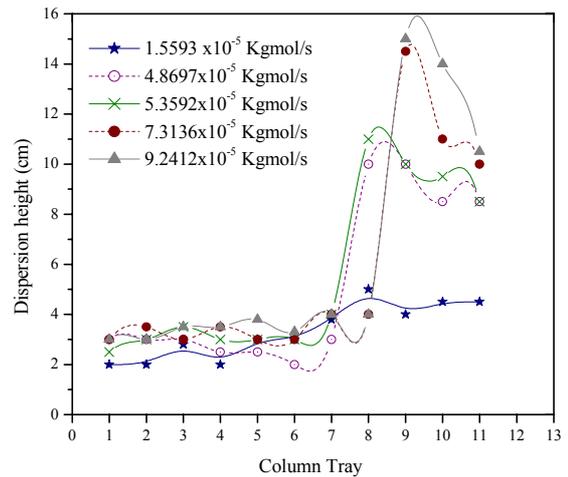


Figure 4. Ethanol concentration and dispersion height profile. Reboiler ethanol mole fraction equal to 2%.

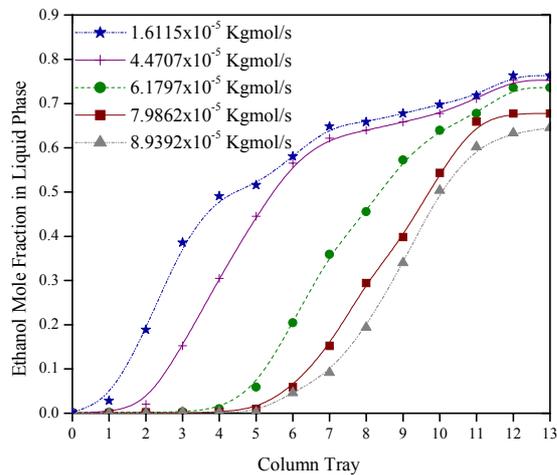


(a) Liquid phase ethanol mole fraction profile

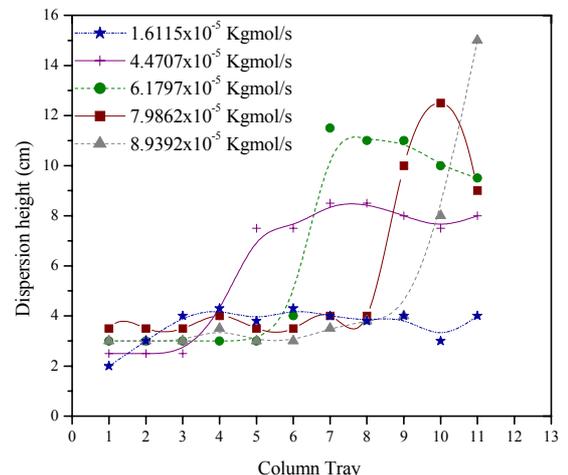


(b) Dispersion height profile

Figure 5. Ethanol concentration and dispersion height profile. Reboiler ethanol mole fraction equal to 3%.



(a) Liquid phase ethanol mole fraction profile



(b) Dispersion height profile

Figure 6. Ethanol concentration and dispersion height profile. Reboiler ethanol mole fraction equal to 4%.

The classic hydraulic model oversimplifies tray action. There are five main flow regimes on distillation trays. These regimes may all occur on the same tray under different liquid and vapor flow rates. Lockett (1986) classified five design types: bubble regime, cellular foam, froth, spray and emulsion. Depending on the tray ethanol concentration and the liquid and vapor flow rates, different regime types may occur on a tray studied. In this investigation, the bubble, cellular foam and froth regimes were observed.

The cellular foam regime was observed in trays with ethanol mole fraction in the liquid phase higher than 0.30 and reflux flow rates lower than 7.00×10^{-5} kgmol/s. For higher flow rates, the cellular foam regime was rarely observed. The division of the vapor stream ensued the occurrence of the cellular foam regime and the bubble regime in contrast with conventional columns.

In trays with ethanol mole fraction lower than 0.30 it was observed the froth regime. At low flows rates (less than 2.00×10^{-5} kgmol/s) the cellular foam regime was well established in trays operating under this regime.

4.2. Murphree Tray Efficiency

Capacity and efficiency are the most relevant column performance parameters. The most important condition to get satisfactory tray performance is to promote a close contact between the liquid and the vapor phases. Tray design requires a combination of theory and experience. Any defective column operation causes a reduction of tray efficiency.

Tray efficiency depends on the mass transfer between the liquid and the vapor; increases in the efficiency is obtained, in general, for long contacting times. Thus, the higher the dispersion height formed on the tray, the higher this contacting time.

The Murphree tray efficiency (E_{MV}) is defined by comparing a real tray with an ideal tray approaches to equilibrium. Lewis (1936) was the first to determine quantitative values for E_{MV} . In case II, exposed by Lewis, vapor is unmixed between trays, and liquid flows in the same direction on successive trays. This case represents the Parastillation column. He noted that case II gives the highest tray efficiency. In this case, for each component:

$$E_{MV(i)} = \frac{y_{o(i)} - y_{o(i-2)}}{y_{eq(i)} - y_{o(i-2)}} \quad (1)$$

which:

$E_{MV(i)}$ - Murphree tray efficiency on tray (i)

$y_{o(i)}$ - Vapor phase ethanol mole fraction leaving tray (i)

$y_{o(i-2)}$ - Vapor phase ethanol mole fraction entering tray (i) [or leaving tray (i-2)]

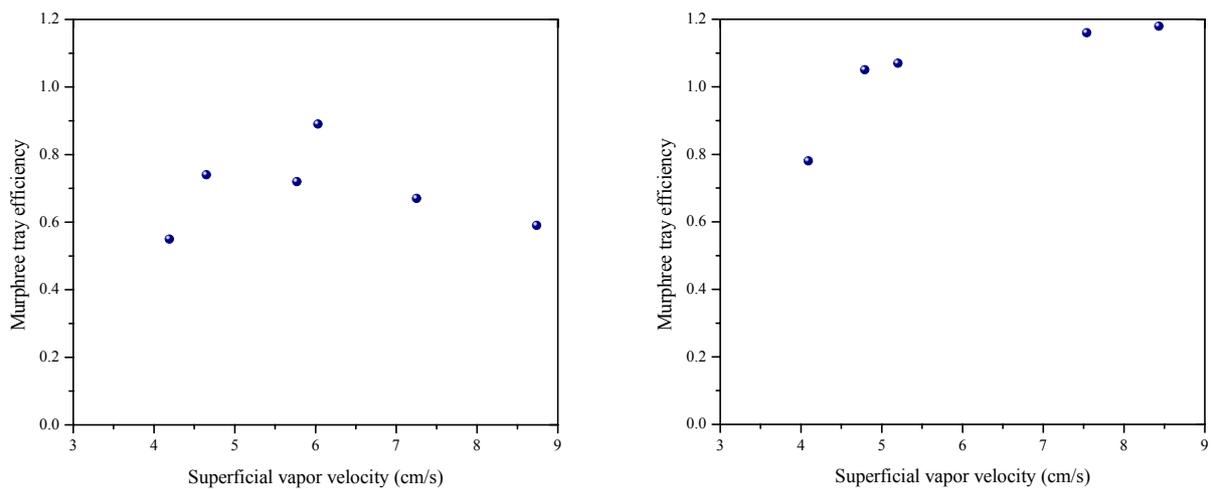
$y_{eq(i)}$ - Vapor phase ethanol mole fraction in equilibrium with liquid phase on tray (i)

As the liquid is never perfectly mixed on the tray (with downcomer) in the horizontal direction, a concentration gradient is established in the liquid as it moves across the tray. This in turn causes a concentration gradient in the vapor leaving the tray. However, Eq. (1) assumes that the output and input vapor streams are perfectly mixed. In favorable circumstances, E_{MV} can exceed 100%.

Murphree tray efficiency for the Parastillation process were calculated and discussed for a wide range of operating conditions. The efficiency depends on many factors, such as vapor velocity, liquid concentration and tray geometry. The efficiency was analyzed on trays where the ethanol mole fraction was in the range of 0.20 to 0.70. Typical experimental results obtained on the Parastillation column are showed in Fig. (7) and (8).

Usually, the efficiency data present great deviations, which results in a cloud of points when plotted. This is caused mainly by the great difficulty in obtaining experimental efficiency data. Figures (7) and (8) also present these deviations. It is important to observe that a mistake in the concentration determination for a tray affects the efficiency determination in adjacent trays.

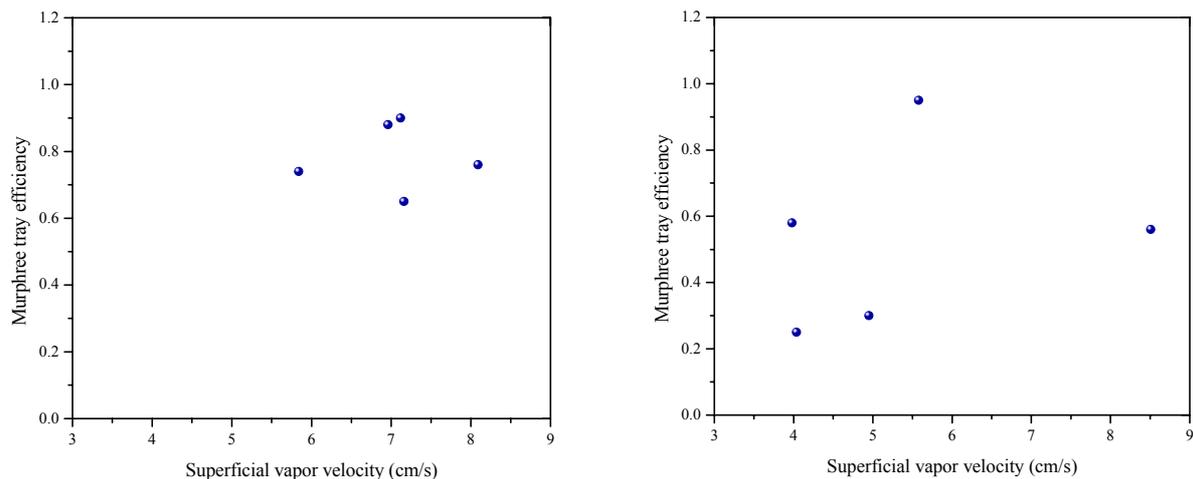
For a given concentration, the efficiency increases with the vapor superficial velocity, until reaching a maximum value, from which it begins to decrease. The extremes correspond to weeping and flooding conditions. Figures (7a) and (7b) show this behavior. In this work, the vapor velocity was changed from minimum to maximum velocities. Weeping usually occurred first on the bottom tray while flooding was usually first observed on the upper trays. It was not possible to operate at all velocities during the experiments. That is the reason why curves in Fig. (8a) and (8b) could not present the expected parabolic behavior.



(a) Liquid phase ethanol mole fraction in a range of 0.20 to 0.30

(b) Liquid phase ethanol mole fraction in a range of 0.40 to 0.45

Figure 7. Superficial vapor velocity versus Murphree tray efficiency.



(a) Liquid phase Ethanol mole fraction in a range of 0.50 to 0.55 (b) Liquid phase Ethanol mole fraction in a range of 0.60 to 0.65

Figure 8. Superficial vapor velocity versus Murphree tray efficiency.

The values of average Murphree tray efficiencies for the data shown in Figs. (7) and (8) were calculated and are shown in Tab.(1).

Table 1. Average Murphree tray efficiency for different ranges of the liquid phase ethanol mole fraction

Range of the liquid phase ethanol mole fraction	Average Murphree tray efficiency
0.20-0.30	0.69
0.40-0.45	1.05
0.50-0.55	0.79
0.60-0.65	0.53

Table (1) indicates that the average Murphree tray efficiency, for the analyzed cases, appears to be strongly dependent on the system properties as well as on the liquid composition on the tray.

The results clearly show that the efficiency values for the Parastillation column tend to be higher for ethanol mole fractions around 0.40-0.45, when compared to the other ranges. For the same superficial vapor velocity range, the efficiency presented a decrease in its average value for fractions around 0.60-0.65.

5. Conclusions

Using an experimental Parastillation column with perforated trays and circular downcomers, the hydrodynamic behavior was determined with an ethanol-water system.

Results indicated that the vapor superficial velocity is an important parameter to be determined for the stable operation of the tray. It was possible to note that an increase of the reflux flow rate leads to higher dispersion heights in the upper trays, causing higher ethanol concentration in these trays.

The results show that the increase of the initial ethanol concentration in the reboiler allowed a higher ethanol distribution along the column trays in function of the reflux flow rate.

In the Parastillation column the cellular foam and bubble regime occurred more often than would be expected for a conventional column.

The effect of the superficial gas velocity on the Murphree efficiency for a perforated tray with downcomer was analyzed. It was verified that the average Murphree tray efficiency appears to be strongly dependent on the system properties as well as on the liquid composition on the tray. The results show that the efficiency values for the Parastillation column tend to be higher for ethanol mole fractions around 0.40-0.45, when compared to the other ranges. For the same superficial vapor velocity range, the efficiency presented a decrease in its average value for fractions around 0.60-0.65.

6. Acknowledgements

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