



## Evaluation of extractive distillation using efficiency correlation and experimental data

## Avaliação da destilação extrativa usando a correlação de eficiência e dados experimentais

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### ABSTRACT

In order to evaluate the behavior of extractive distillation columns efficiency was used the correlation developed by Barros & Wolf, which considers the mass and heat transfer parameters, based on the physical and thermal characteristic of ideal and non-ideal liquid mixtures. The results obtained from Barros & Wolf correlation efficiency were compared with the experimental data obtained by Meirelles. For all cases studied, the solvent used to separate each mixture, reflect on the efficiency values in extractive distillation column. Those factors are more strongly when the interaction between the liquid and vapor phase in the column promote the turbulence, factor predominant on mass and heat transference. The correlation used here shows good approximation when the data from this correlation were compared with that from real profile data obtained by Meirelles, for extractive distillation column. The precision of this correlation is due the mass and heat phenomenon are involved in real process and the behavior efficiency along of distillation column is similar that described in the literature. For this, due the high complexity associated with carried out experiment in laboratory, the correlation used here can be explore to evaluate the profile of extractive distillation operations.

**Keywords:** efficiency, correlation, barros&wolf, extractive distillation.

### RESUMO

Para avaliar o comportamento da eficiência das colunas de destilação extrativa foi utilizada a correlação desenvolvida pela Barros & Wolf, que considera os parâmetros de massa e transferência de calor, com base nas características físicas e térmicas das misturas líquidas ideais e não ideais. Os resultados obtidos com a eficiência da correlação Barros & Wolf foram comparados com os dados experimentais obtidos por Meirelles. Para todos os casos estudados, o solvente utilizado para separar cada mistura, reflete sobre os valores de eficiência na coluna de destilação extrativa. Esses fatores são mais fortes quando a interação entre a fase líquida e de vapor na coluna promove a turbulência, fator predominante na transferência de massa e calor. A correlação utilizada aqui



mostra uma boa aproximação quando os dados desta correlação foram comparados com os dados de perfil real obtidos por Meirelles, para a coluna de destilação extrativa. A precisão desta correlação se deve ao fato de que o fenômeno massa e calor estão envolvidos no processo real e a eficiência do comportamento ao longo da coluna de destilação é semelhante à descrita na literatura. Para isso, devido à alta complexidade associada à experiência realizada em laboratório, a correlação aqui utilizada pode ser explorada para avaliar o perfil das operações de destilação extrativa.

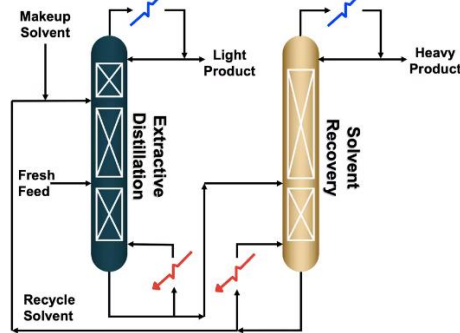
**Palavras-chave:** eficiência, correlação, barros&wolf, destilação extrativa.

## 1 INTRODUCTION

The extractive distillation is special technique where the solvent with greater bubble point is added in the mixture to alter the relative volatility of the components due its similarity in the vapor pressure or azeotropic mixtures formation. The absence of heterogeneous azeotropic and the easy recovery of the solvent by means of fractional distillation give the extractive distillation processes more simplicity than the azeotropic distillation. When the extractive distillation columns are used, the solvent feed position is located always on the some plates of the top. The solvent flow, the reflux rate and the feeding thermal conditions are chosen in way having the wanted profile solvent concentration in the column (Noriler et al, 2009 and Reis et al, 2006). The concentration should promote a satisfactory difference among the relative volatility of the key components, but it should avoid the formation of two liquid phases in any plate.

The results of those factors shows that the efficiency of mass transfer in extractive distillation processes are generally lesser than the efficiencies observed in ordinary distillation. The extractive distillation is a process with high flexibility and with operational simplicity. The two columns involved in the process are practically independent one of the other and due to the low vapor pressure, solvent can't contaminate the top product (Wolf Maciel et al (2001); Barros and Maciel (1998).

Figure 1: Characteristic of Extractive Distillation Unity



The absence of experimental data in the literature about the efficiency boosted the study and development of Barros and Wolf correlation efficiency used to know the profile of this parameter along of the distillation column, related to each component in the mixture and for each plate. The results from these studies were validated using experimental data obtained by Meirelles (Meirelles, 1992 and Barros, 1997). The results from this studies showed the accuracy and relevant, in term of profile of extractive distillation column and mass and heat transference.

### 1.1 EFFICIENCY CONCEPTS

The efficiency concepts developed for extractive distillation are the same used for conventional distillation column, but until now didn't develop news study to improve the quality of this correlation. To better understanding this process, Barros (1997) developed the correlation used in the literature to display the relevance of these operational parameters to knowingly the real performance of efficiencies in this equipment.

The overall efficiency, for distillation columns, was defined by Lewis (1922), as the relation between theoretical and real plate required performing a given separation. The limitations of this definition is that the computational efficiency based on this equation show problems to determining the number of theoretical plates required for give experimental separation. So, the experimental data and mathematical model are not very realistic for the application in distillation processes.

In 1925, Murphree defined the plate efficiency, relating the behavior of a real with an ideal plate through of the contact degree between the vapor and liquid phases. In this definition, the efficiencies for the vapor and liquid phases are



generally different for the same plate. For this, its application is limited. The definition of the point efficiency was developed by West et al (1952) and it is larger fidelity to studies the plate efficiency. Many other definitions for efficiencies were presented, as one developed by Medina et al. (1978), Holland (1980), Hausen (1953), among others, but all that presented modification to correct the Murphree's definition, but neither represented better when compared with the efficiency proposed by Murphree.

The first correlation equation for efficiency proposed in the literature was developed by Drickamer and Badford in 1943 for bubble cap trays column (Equation 1).

$$\eta_{oc} = 0.17 - 0.616 \text{Log}_{10} \sum(x_i \mu_L) \quad (1)$$

Where  $x_i$  is the molar fraction of more volatile component in the feed position and  $\mu_L$  is the liquid viscosity in the feed position.

For other hand, O'Connell proposed other efficiencies correlation for column with bubble cap trays, which can be represented accord Equation (2).

$$\eta_{oc} = 48,7663 \left( \alpha_{LK} \mu_{\text{cmB}^a} \right)^{-0.255837} \quad (2)$$

Where  $\mu_L$  is the liquid viscosity in mPa-s and  $\alpha$  is the relative volatility. The O'Connell equation is commonly used to determination of efficiency in real distillation column, mainly when the hydrocarbons mixture are involved in separation processes.

To improve the quality of results, Chu (1951) proposed other correlation for performed trays, who's represented by Equation 3.

$$\text{Log}_{10} \eta_{oc} = 1.67 + 0.3 \text{Log}_{10} \left( \frac{L}{V} \right) - 0.25 \text{Log}_{10} (\mu_L \alpha) + 0.092 h_i \quad (3)$$

The correlation *proposed* by Chu include the level of liquid on the plate, condition that incorporate the contact time *between* liquid and vapor phase. The



equation proposed, consider too the flowrate of liquid and vapor phases, viscosity and relative volatility of the phase in contact between on the plate.

The AIChE (1958) method is the most detailed method for predicting plate efficiencies that is available in the open literature. It takes *into* account all the major factors that are known to affect plate efficiency. Equation below shows the number of gas phase transfer units.

$$\eta_{OG} = 1 - e^{-N_{OG}} \quad (4)$$

Where *NOG* is the overall number of transfer units for the gas phase defined by Equation (5). *NG* and *NL* are the number of transfer units in the gas and liquid phases, respectively, and  $\lambda$  is the stripping factor calculated as  $\lambda = mG/L$ . In this case, *m* is the slope of the equilibrium line and *G* and *L* are the gas and liquid flowrates per cross-sectional bubbling area in kmol/m<sup>2</sup>-s.

$$\frac{1}{N_{OG}} = \frac{1}{N_G} + \frac{\lambda}{N_L} \quad (5)$$

The approach to equilibrium that can be achieved with a given number of transfer units depends on the concentration profile. The driving force for mass transfer, which, in turn, depends on the flow pattern of the vapor and liquid phases. Most models for cross-flow trays assume that the vapor flows vertically in plug flow and the liquid is vertically well-mixed.

Chaiyavech and Van Winkle developed in 1961 the correlation for efficiencies for perforated plate, that consider the surface tension, liquid viscosity, diffusivity, specific mass and relative volatility as imports parameters to know the efficiencies values.

$$\eta_{oc} = 0.0691 \left( \frac{\sigma}{\mu_L V_r} \right)^{0.64} \left( \frac{\mu_L}{\rho_L D_r} \right)^{0.19} (\alpha)^{0.056} \quad (6)$$

In 1965 Eduljee developed the efficiency correlation as function of relative volatility and viscosity as parameters related (Equation 6).

$$\eta_{oc} = 51 - 32.5 \text{Log}(\mu_L \alpha) \quad (6)$$



Macfarlant (1972) developed the efficiency correlation as function of Smith number (Sc) and Reynolds number (Re) parameters

$$\eta_{\alpha} = 0.086(\text{Re} \cdot \text{Sc}^{0.1})(D_g \cdot \text{Sc})^{0.15} \quad (7)$$

In the same way, English and Van Winkle developed in 1983 the correlation that consider the Smith number (Sc), Reynolds number (Re) and diffusivity as important parameters to evaluate the efficiency, accord Equation (8).

$$\eta_{\alpha} = 0.07 D_g^{0.14} \text{Sc}^{0.25} \text{Re}^{0.08} \quad (8)$$

All those correlations were developed to determination of plate number need give the real plate needed when the number of theoretical plate were knowngle.

The procedures used for project of extractive distillation column are similar to those used in the conventional distillation and that the extractive distillation involves mixture with azeotropic point. For this process the solvent is feed in the column to modify the mixture thermodynamic parameters. The plate to feed solvent in extractive distillation is located in the top column, so that the solvent rate, the reflux rate and the feed thermal conditions are chosen to obtaining the concentration profile in the column. This concentration should promote a satisfactory difference between the volatility of components, but it should avoid the two liquid phases formation in any plate and maintain the demands of heat sensitive (Barros and Wolf Maciel, 1997).

The end result of this set procedure is the efficiency of mass transfer in the extractive distillation processes. Gerster (1969) and Weiss and Arlt (1987) observed that the efficiencies in the extractive distillation columns are generally smaller than the efficiencies observed in conventional or ordinary distillation. Gerster justifies the smallest efficiency due to liquid flow rate increase with decrease the contact time between the liquid and vapor phases in the plate of distillation columns. To Weiss and Arlt, the efficiencies are reduced due to the decrease of interfacial area, caused by the extractive agent's (King, 1980).

The effects of heat transfer are neglected in the velocity of mass transfer





when the equilibrium stage model is used. This fact can be observed in the A.I.Ch.E. Bubble-Tray Design Manual (1958), considered the most complete analysis to study of the plates efficiencies. Kirschbaum (1940) suggested evaluate the distillation plates efficiencies as function of heat transfer between liquid and vapor phase. Liang and Smith (1962) considered the interaction between heat and mass transfer as possibility to: a) excluding the possibility of extensive superheating in the bulk of the liquid or sub cooling in the bulk of the vapor phase; b) additional mass flux terms must be added to the diffusional mass flux equation to account for the condensation of vapor and the vaporization of liquid in the bulk of the respective phases.

These effects should be considered separately. The balance in the distillation process caused by the evaporation and condensation, result of the simultaneous mass and heat transfer and an abrupt effect observed due usually its greater values of the latent vaporization heat. In the absence of the heat transfer, the interfacial composition has been values whose mass flow is the same in each phase, to avoid the accumulation in the interface. Similarly, in the absence of mass transfer, the temperature interfacial to tend the values to allow the same velocity of heat transfers in the interface. Thus, the temperature in the interface is the average of the two phases multiplied by the heat transfer coefficient of each phase.

The heat transfer coefficient in the liquid phase is substantially larger than the heat transfer coefficient in the vapor phase, due to the high thermal conductivity of the liquid phase. Thus, the temperature in the interface will be closer to the temperature of the liquid phase (Pescari, 1996). To maintain this condition, occur the evaporation or condensation in the interface to obtain the different heat flows between the phases. As the heat transfer coefficient in the liquid phase is larger than the vapor phase, great heat flows occur in the liquid interface when compared with the vapor interface. Therefore, the condensation in the interface appears, allowing the heat elimination through the liquid phase. These condensations affects the mass and heat transfer coefficients in the liquid and vapor phases and produce the superheating in the liquid phase (Barros, 1997).

Experimental data obtained by Liang and Smith (1962) and others, showed that the plate and the column efficiencies increase with the composition when the



temperature is higher. Thus, the increase of efficiency is interpreted as function of the simultaneous mass and heat transfer. When the thermal forces are great, the gradients of surface tension are also great, due to the effect of the viscous flow rate. Therefore, in the distillation process the surface tension affects the mass and heat transfer.

## 1.2 MASS AND HEAT TRANSFER CONCEPT

The products purity, in an extractive distillation column, is influenced, strongly, by the geometry and column design to generate the phase mixture intensity obtained by interaction between the internal flow rate vapor - liquid phase and the type of solvent in the separation processes.

The distillation processes occur with the mass and heat transfer between both the liquid and vapor phase. The phases interaction in the separation column is not characterized of the thermodynamic equilibrium between the streams leaving any particular stage. The velocity of interfacial mass transfer controls the degree of remotion in each phase, which is reflected in the molecular diffusion phenomenon. It is necessary that the velocity heat transfer is considered to ponder the mass remotion of the system in relation of the mass transfer effects.

The diffusional mass transference of component, for binary mixture, in the liquid or vapor phase should happen in direction to decrease of the partial pressure or to decrease the concentration of the component. These coefficients are defined as function of the velocity mass transfer of a given component in a mixture through the interface.

For any real separation, it is necessary to correct the obtained values, based on the concepts of ideal separation factors to consider the effects of entertainment, plug flow, column design and limitations of mass and heat transfer. When the equilibrium data are known, it is convenient to use the efficiency concept as approach measure, because that is a parameter governed by the processes of mass transfer in the plates (Barros, 1997).

The absence of the heat transfer in the distillation column the interfacial composition give the values whose mass flow is the same in the phase, to avoid the accumulation in the interface. Similarly, in the absence of mass transfer, the interfacial temperature tends to values that allow the same speeds of heat transfer





to interface. The interface temperature is the average of the temperatures of the two phases, multiplied by the heat transfer coefficient of each phase. The heat transfer coefficient in the liquid phase is substantially larger than the vapor phase, due to the high thermal conductivity of the liquid phase and the interface temperature will be closer to the temperature of the liquid phase.

The correlation developed by Chilton-Colburn (Bird et al., 1960) show this performance. To the liquid phase, the penetration theory was used, emphasized that in many situations the time of exposure of a fluid to mass transfer is short, so that the concentration gradient of the film theory, characteristic of steady state, would not have time to developed, accord the Equation 9 for liquid phase.

$$h_L = K_L \cdot C_{pL} \sqrt{\frac{\alpha}{D_{ab}}} \quad (9)$$

Where the thermal diffusivity  $\alpha$  was defined through the Equation (10)

$$\alpha = \frac{k_L M_L}{r_L C_{pL}} \quad (10)$$

The heat coefficient for the vapor phase was defined by Equation (11).

$$h_V = K_V \cdot C_{pV} Le_V^{2/3} \quad (11)$$

Thus, the Lewis number ( $Le_V$ ) was calculated accord the Equation (12)

$$Le_V = \frac{k_V \cdot M_V}{r_V C_{pV} D_{ab}} \quad (12)$$

When the heat and mass transfer happen simultaneously, the interface composition and temperature reach to equilibrium through the evaporation and condensation in the interface. As the heat transfer coefficient in the liquid phase is larger than the vapor phase, as described previously, they happen larger heat



flows in the interface liquid when compared with the interface vapor. Therefore, the condensation appears in the interface allowing liberation of the heat that is eliminated through the liquid phase. This condensation affects the heat and mass transfer coefficients in the distillation processes and it tends to produce the superheating in the liquid phase.

## 2 METHODOLOGY

To determine the behavior of the components mole fractions along of extractive distillation column, Meirelles et al. (1992) developed an experimental study using a column with 60 plates, which the feed position of the azeotropic mixture (ethanol-water) was located in the plate 31 and the feed position of the solvent (ethylene glycol) located in the plate 3 (from top to bottom of the column). The experimental data obtained by Mereilles was compared with the profile obtained through the efficiency correlation developed by Barros and Wolf. The operation conditions of two experiments, developed by Meirelles, are described in the Table 1.

Table 1: Systems used and its characteristic

SYSTEMS	NST	Tray Feed	Feed (mol/h)	Flow	Feed Molar Fractions	Distillated Flow(mol/h)
Ethanol, Water	25	7	100,00		0,80; 0,20; 0,00	78,80
Ethylene -Glycol (Solvent)		22	80,00		0,00; 0,00; 1,00	

Ethylene glycol was the solvent used by Meirelles (1992). The proportions of the ethylene glycol in the mixture were described in Table 2. The feed conditions used also are presented in the Table 2.



Figure 2: Experimental data used by Meirelles (Meirelles et al., 1992)

Exp.	Feed Binary Mixture	Feed Flow Rate Mixture (mol/h)	Feed Flow Rate Solvent (mol/h)	Distillated Flow Rate (mol/h)	Reflux Ratio (RR)	Molar Fraction Feed solvent	Molar Fraction Distillate (XD)
1	0,862; 0,136	39,78	44,69	32,64	1,07	0,9930	0,996
2	0,850; 0,150	61,83	44,69	50,19	1,50	0,9958	0,995

The equation of profile efficiency developed to extractive distillation column was described as a function of the mixture properties, as such as the mixture thermal conductivity ( $k$ ), mixture density ( $\rho$ ), mixture calorific capacity ( $cp$ ), mixture viscosity ( $\mu$ ), average molecular weight ( $M$ ) and mixture diffusivity ( $D_{i,j}$ ), as indicated in the Equation (13).

$$h_i = 19.37272 \frac{k}{cp} \frac{D_{i,j}}{m^2} r M^{-0.109588} \quad (13)$$

Where  $\eta_i$  is the tray efficiency. For the determination of the components profile efficiency, the same correlation was used, operated now with pure components parameters.

### 3 RESULTS AND DISCUSSIONS

#### 3.1 PROFILE EFFICIENCY

The components efficiency profiles obtained to extractive distillation have strong disturbances in the feed position, and its values increase from the top to the bottom of the column. For the system studied, the maximum values of efficiency are located between the feed key components and the feed solvent. This behavior shows the influence of mass and heat transfer coefficients in the feed positions, because the strong interaction between the liquid and the vapor flows against the feed flows rate, generating the disturbances in the values of the efficiency.

As the solvent flows only in the liquid phase along of the distillation column, for the system studied, provides larger values of the efficiency for this component because the mass transfer in the extractive distillation processes is controlled by the liquid phase. For the system evaluated here, the more volatile component efficiency gives smaller values efficiency when it is compared with the values of efficiencies of the solvent components.

The permanence of the solvent in the liquid phase along the distillation



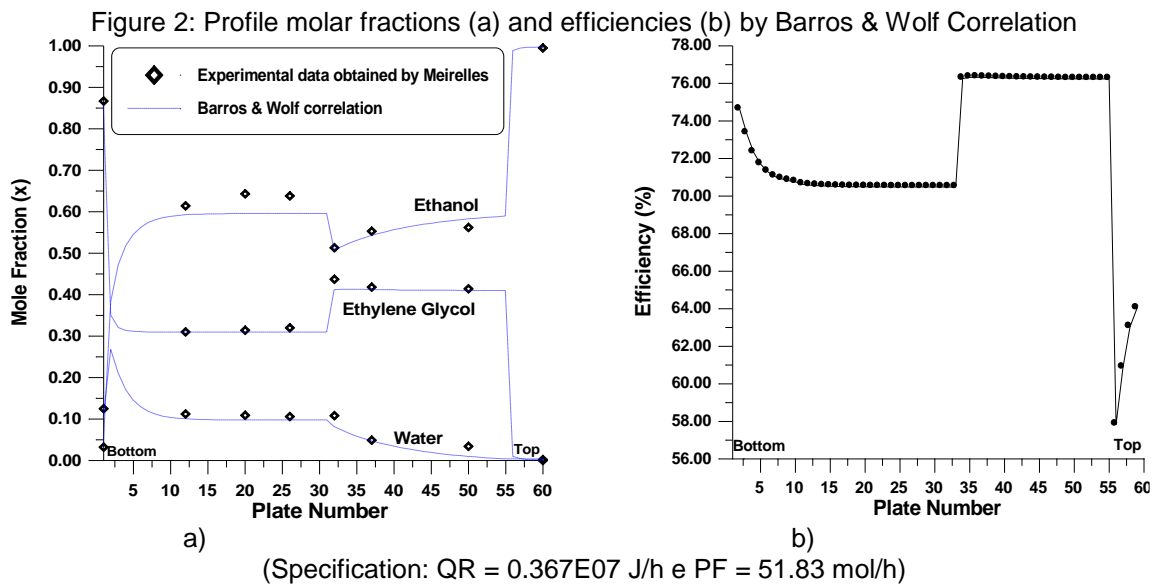
column, give larger values of the efficiency for this component along of the distillation column because the mass transfer in this process is controlled by the liquid phase. In this case, the more volatile component efficiency has smaller values efficiency when compared with the efficiency of the solvent and with the plate efficiency.

The influence of the disturbances reflux rate (RR), parameter of great relevance in the internal liquid and vapor flows, and consequently in the mass and heat transfer coefficients in the extractive distillation processes, it was evaluated in this work and the results show great disturbances of the efficiency with the disturbance of the specified reflux rate for the two systems. It can be observed that the larger reflux rate specified gives larger efficiency along of the distillation column, due the increase of the interaction between the internal flows, parameters evaluate in the efficiencies correlation through the mixture parameters.

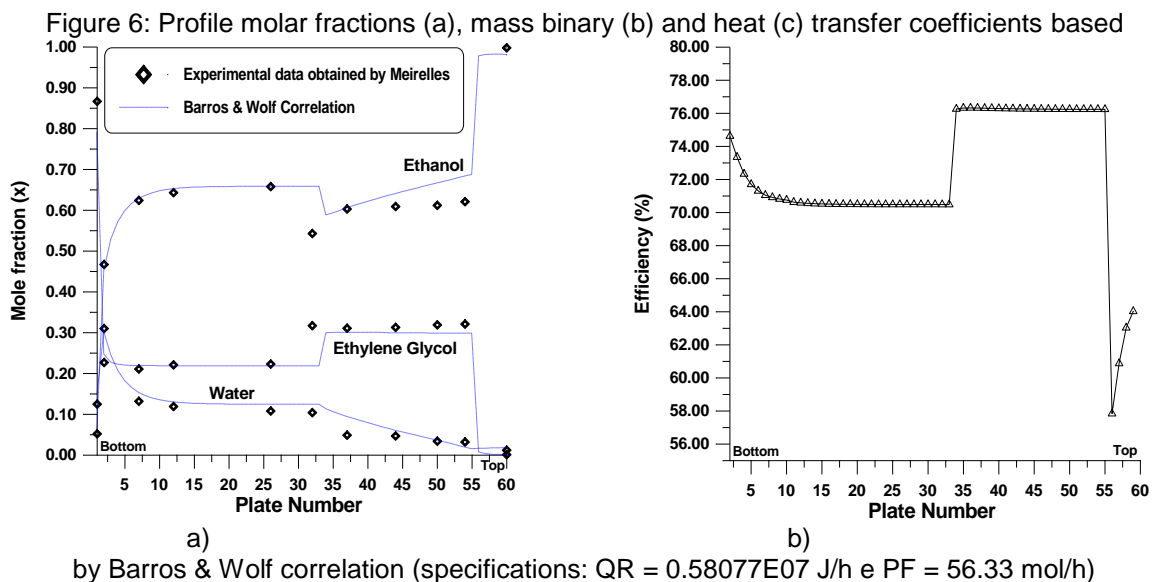
### 3.2 CORROBORATION WITH EXPERIMENTAL DATA

The experimental data (Experiment 1), described in the Table 1, was used to simulate the extractive distillation column with the Barros and Wolf correlation. With the results obtained was evaluated the profiles efficiency and the binary mass and heat transfer coefficients along of the distillation column (Figure 2). For the comparison between experimental and simulate data it is possible to observe an excellent approach along the distillation column.

The behavior of the efficiency described in the Figure 2 (b) shows a strong disturbances in the feed positions and, generally, the efficiencies increases from the top to the bottom of the column, with points of maximum efficiency is located next to the two feedings positions. Below the feed position, the efficiency increases to the bottom column. This behavior is similar to the binary ethanol/water mass transfer coefficients and inverse to binary ethanol/ethylene glycol mass transfer coefficients. There is also a behavior similar between the efficiency and mass and heat transfer coefficients profile evaluated in the Figure 2-b, what justifies the influence of mass and heat transfer in the diffusional processes and in the mass transfer efficiency. The experimental and the developed correlation data show great agreement (Figure 2 - a).



The behavior of the mole fractions profile obtained based on the experiment 2 data were similar to the results of the experiment 1, so much for data from of the component and plate efficiency. The behavior of the binary mass and heat transfer coefficients of the ethanol/water systems show similar to the behavior of the distillation column efficiency (Figure 6-b). The agreement between the simulate and experimental data in this case was also good (Figure 6-a).



## 4 CONCLUSIONS

Based on results obtained in this work, we can conclude that:

- The correlation used in this work have the capacity to relate the most influential parameters in the extractive distillation processes;



- b) Besides, it is fundamental to present in a concise way the behavior of the efficiency in the extractive distillation column considering all the phenomenon evaluated in the real processes;
- c) The developed correlation allows the analysis of the separation processes through detailed behavior efficiency study in the extractive distillation column;
- d) To the systems studied, the plate and components efficiency increases from the top to the bottom of the column, with the disturbances in the feeding regions are from strong interactions between internal and feed flows;
- e) The presence of the solvent in a extractive distillation column provides larger mass and heat transfer coefficients due the interactions between the phases;
- f) The comparison between Barros & Wolf correlation efficiency with the experimental data obtained by Meirelles shows a medium mistake of 2,5%. Larger and smaller mistakes were observed for different components and for different experiments;
- g) The behavior of the efficiency in the distillation column resembles to the behavior of the heat transfer coefficients and of the binary ethanol/water mass transfer coefficients, dependent of the used specification;
- h) The specifications used to simulation of the extractive distillation column influence in the behavior of the efficiency. Generally, strong disturbances are observed in the feeding positions;
- i) It is possible to analyze the behavior of the profile efficiency through of the mass and heat transfer coefficients once these parameters are the ones that most influence the behavior of the efficiency, and they are dependent on the physics characteristics of the system, of the contact time between liquid and vapor phases and the strong interactions between liquid, vapor and feed load in the column.

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### DECLARATION OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

### NOMENCLATURE

K : Thermal conductivity of mixture (w/cm.k)  
 $\rho$  : Density of mixture (g/cm<sup>3</sup>)  
D<sub>ij</sub> : Mass diffusivity of mixture (cm<sup>2</sup>/s)  
M : Average molecular weight (g/mol)  
C<sub>p</sub> : Heat capacity of mixture (J/mol.k)  
 $\mu$  : Viscosity of mixture (cP)  
SC: Smight Number  
Re: Reynolds Number



## REFERENCES

A.I.C.h.E., "Bubble-Tray Design Manual"; American Institute of Chemical Eng. New York, 1958.

BARROS, A. A. CHIVANGA "Desenvolvimento de modelo dos estágios de não equilíbrio e proposição de correlações de eficiência para os processos de destilação convencional e extrativa", PhD Thesis; LDPS, DPQ, FEQ, UNICAMP, BRASIL, agosto de 1997.

BARROS, A.A.CHIVANGA, MACIEL, M.R; "Uso da modelagem dos estágios de não equilíbrio para a avaliação da nova correlação da eficiência das colunas de destilação"; 1º Congresso de Engenharia de Processos do Mercosul, Setembro, 1997.

Barros, A. A. C.; Wolf MACIEL, M. R.; Aplicação da Modelagem de Estágios de Não Equilíbrio na Avaliação da Nova Correlação da Eficiência das Colunas de Destilação, 12º; Congresso Brasileiro de Engenharia Química; Porto Alegre, Brazil; 1998.

Bertoli, Sávio L.; Kalvelag, Pollyana M. S.; Albuquerque, Allan A.; Barros, A. A. C.; (Vapor + Liquid) Equilibrium for Mixtures Ethanol + Biodiesel from Soybean Oil and Frying Oil; International Journal of Thermodynamics (IJoT) 20, 159-164; 2017.

Bird, R. B., Stewart, W. E., & Lightfoot, E. N.; Transport Phenomena. New York: John Wiley & Sons, Inc.; 1960.

Chaiyavech and Van Winkle; The University of Texas, Austin, 12, Tex. 53, 3, 187-195, 1961.

CHU, J. C.; Plate efficiency correlation in distilling columns and gas absorbers. J. Appl. Chem., 1(12), 529-541, 1951.

DRICKAMER, H. G., BRADFORD, J. R. Overall plate efficiency of commercial hydrocarbon fractionating columns as a function of viscosity. Trans. AIChE, 39,319-360, 1943.

GERSTER, J. A.; "Azeotropic and Extractive Distillation", Chemical Engineering Progress; 65 (9), 43-46, 1969.

GERSTER, J. A., HILL, A. B., HOCHGRAF, N. N., ROBINSON, D. G. Tray Efficiencies in Distillation Columns. AIChE Research Committee, University Delaware, Newark, 1958.

HAUSEN, H.; Chem. Ing. Tech. 25; 595; 1953.

HOLLAND, C.D."Computing Large Negative or Positive Values for the Murphree Efficiencies". Chemical Eng. Science, 35(5); pag. 2235; 1980;

KING, C.J., "Separation Processes", 2nd Edition, McGraw Hill Inc. (1980).



KIRSCHBAUM, E.; "Destillier und Rektifiziertechnik", Springer - Verlag, Berlin, 1940.

LEWIS, W.K. "The Efficiency and Design of Rectifying columns for Binary Mixtures". J. Ind. Eng. Chem.; 4(6). 492-497, 1922.

LIANG, S. Y., e W. SMITH; Chem. Eng. Sci., 17:11; 1962.

MEDINA, A. G., ASHTON, N., MCDERMOTT, C. Murphree and vaporization efficiencies in Multicomponent distillation. Chem. Eng. Sci., 33 (3), 331-339, 1978.

MEIRELLES, A. J. WEISS, S. and HERFURTH, H.; "Ethanol Dehydration by Extractive Distillation"; J. Chem. Tech. Biotechnol., 53, 181-188; 1992.

MURPHREE, E.V. "Rectifying Column Calculation", Ind. Eng. Chem., 17(7); 1925; pag. 747-750.

Noriler, Dirceu; Meier, HF; Barros, AAC; Maciel, MRW; Prediction of efficiencies through simultaneous momentum, mass and energy transfer analyses in a distillation sieve tray by CFD techniques; Computer Aided Chemical Engineering 27, 1167-1172; 2009.

NORILER, Dirceu; DUARTE, Elis Regina; BARROS, António André Chivanga; AVALIAÇÃO DE PARÂMETROS DE DESTILAÇÃO EXTRATIVA POR SIMULAÇÃO NUMÉRICA; Revista Evidência Multidisciplinar, 12, 1, 2012.

O'CONNELL, H. E. Plate efficiency of fractionating columns and absorbers. Trans. AIChE, 42, 741- 755, 1946.

PESCARINI, M. H., "Desenvolvimento de um Algoritmo para a Simulação de Colunas de Destilação Multicomponente em Estado Estacionário Utilizando a Modelagem de Estágios de

Reis, MHM; Barros, A.A.C; Meirelles, AJA; Filho, RM; Wolf-Maciel, MR; Application of plate and component efficiency correlations in homogeneous azeotropic distillation processes; Industrial & engineering chemistry research 45 (16), 5755-5760; 2006.

Soares, Cíntia; Noriler, Dirceu; Barros, AAC; Meier, HF, Wolf, Maciel MR; Numerical Simulation of Liquid Flow On a Distillation Tray; Iberian Latin-American Congress On Computational Methods In Engineering and Brazilian Congresso on Computational Mechanics, 22, 2001

Soares, Soares; Barros, A. A. C., Wolf-Maciel, M. R.; Simulation of a sieve plate column with ethanol/water system using the nonequilibrium stage model; Chemie Ingenieur Technik 73 (6), 724-724; 2001.

Soares, Cíntia; Noriler, Dirceu; Chivanga Barros, A A.; Meier, Henry França; Wolf-Maciel, M. R.; Computational fluid dynamics for simulation of a gas-liquid flow on a sieve plate: Model comparisons, Proceedings of 634th Event of the European Federation of Chemical Engineering, CD-ROM, 2002



Soares, Cintia; Noriler, Dirceu; Wolf Maciel, M. R., Chivanga Barros, A. A.; HF Meier; Verification and validation in CFD for a free-surface gas-liquid flow in channels; Brazilian Journal of Chemical Engineering 30, 323-325; 2013.

WEISS, S. and ARLT, R.; "On the Modelling of Mass Transfer in Extractive Distillation"; Chemical Engineering Process, 21, 107-113, 1987

WEST, R. G., GILBERT, W. D., SHIMIZU, T. Mechanism of mass transfer on bubble plates: plates efficiencies. Ind. Eng. Chem., 44 (10), 2470-2478, 1952.

Wolf-Maciel, MR; Soares, C; Barros, AAC; Validations of the nonequilibrium stage model and of a new efficiency correlation for non-ideal distillation process through simulated and experimental data Computer Aided Chemical Engineering 9, 321-326; 2001.