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Modelling of Heat and Mass Transfer in the Evaporation of a Binary Mixture in a Falling Film Apparatus

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Abstract: A research on a mathematical modeling of simultaneous heat and mass transfer during the process of the evaporation of a saturated binary mixture of n Hexane-Toluene flowing down a tube has been carried out. The flow is characterized by a falling liquid film and the film theory model is used. The geometry retained is a cylindrical column with a smooth uniform heat flux. The objective of the study is to investigate the sensitivity of flow, heat and mass transfer parameters. Functioning and designing of this process on constant transfer parameters will be discussed. The findings show that a higher dependency on the liquid phase parameters along the column height, phase compositions and flux density are found. A further study of the variation of the transfer parameters as a function of the internal flow, composition and chemical properties could be introduced to the given model to establish a model behavior.

Key words: Falling vertical liquid film % Evaporation % Heat and mass transfer % Binary mixture

INTRODUCTION

Falling film evaporator's concentrators are one of the technological methods which have been extensively used in the chemical process and other industries. These evaporators are used for heat and mass transfer purposes like pharmaceutical applications; food concentration (sugar and syrups, fruit juices and others), ammonium nitrates, wetted wall for rectification and gas absorption, desalination process and in the treatment of wastes gases power generation, energy, petrochemicals refrigeration and other heat sensitive materials. Also found in Ocean thermal power energy conversion pilot plant systems, absorber and vapor generators systems [1-7].

This apparatus may also be used in the form of gas liquid reactors and characterized by the effects of higher interactions between the hydrodynamic conditions on the energy and mass transfer in within the phases. It can be designed for a low temperature difference where the falling film evaporators are the most effective. A small pressure drop caused a low temperature difference and a short contact time between the heating surface and the liquid to be evaporated. This is very useful for working with the heat sensitive materials. The efficient utilization of a heat transfer medium is very important for designing heat and mass purpose as well as for the economical purpose.

The study is on the process of separation of a saturated binary mixture flowing downwards a vertical smooth cylindrical tube heated by a uniform flux. This flux is provided by the electromagnetic induction without the traditional boiler equipment used in the conventional process as shown in Figure 1. In this type of equipment, the process of evaporation with the enriching of the vapor phase composition of the volatile component instead of the process of rectification has been achieved. The suppression of the boiler enhanced

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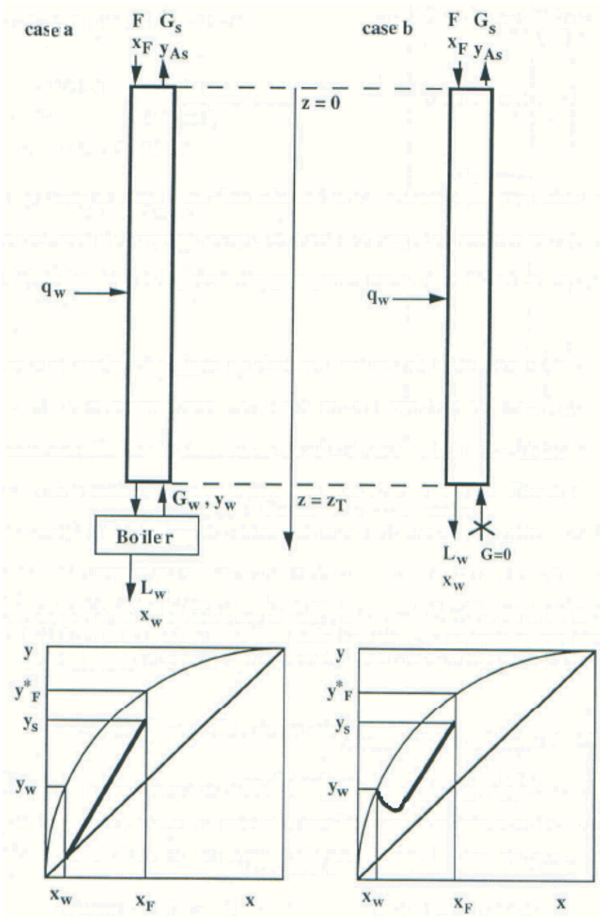

Fig. 1: Comparison between the conventional process (case a-with boiler and rectification) and the study case (case b-no vapor flow at the bottom and evaporation)

the system overall efficiency. This is also due to the fact that the imposed power flux is supplied directly on the falling liquid film by the electromagnetic induction that reduced the conduction losses in the conventional energy transfer. The objective of this study is to investigate the influence of the imposed power on the heat and mass transfer parameters.

MATERIALS AND METHODS

In this study, some major specifications for this type of evaporation process are in a steadily state flow of condition. All of the energy is considered to be transmitted to the liquid film in order to achieve the evaporation process at the gas liquid interface by surface evaporation. The gas flows at the bottom of apparatus should be considered null. The surface area for the heat and mass transfer between phases should be equaled. The last differential element of the height of column provides the equilibrium state between the vapor generated in this element and the liquid film leaving the bottom of the apparatus. The flow is in the same direction in within phases with negligible conduction between the two phases and the contribution of conduction and convection components in the mass and heat transfer are retained.

The mathematical model has been established based on the basis of the exchange of mass and energy between the liquid film and the wall (uniform energy flux applied, q_w, in watt per meter of height) for a differential element height dz as in Figure 2.

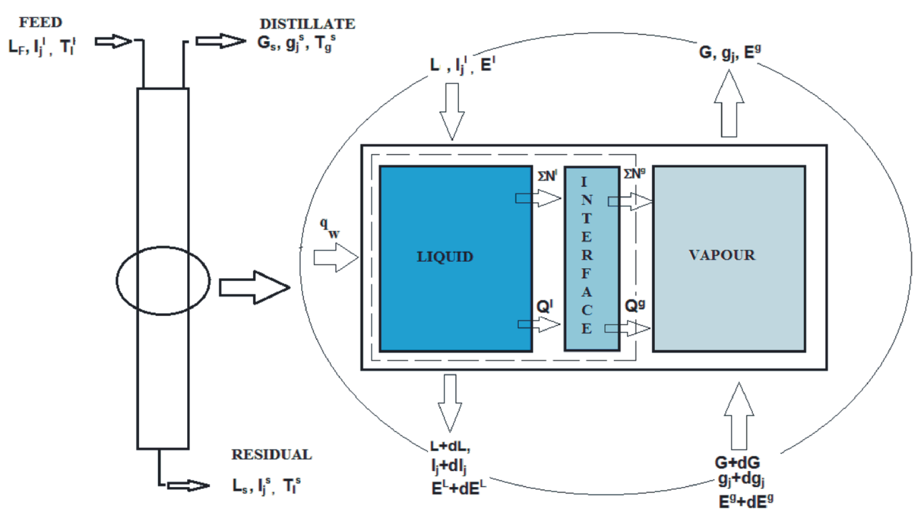

Fig. 2: A schematic representation of the apparatus and one element dz of contact and the mass and energy balanceG2

The exchange between the phases is accomplished through the gas liquid interface which is proposed without having accumulation of mass and in a thermodynamic equilibrium. The chosen model was established to investigate the evaporation of several components in the liquid and vapor phase. In this study, there are only two components present in the given phase, taking into account of the counter current circulation of these components as shown in Figure 2.

In order to satisfy the system equations, the equations of conservation of mass and energy as well as the boundary conditions and flux of mass have been added. The heat and mass transfer coefficients have been corrected for a finite quantity of flux as given by the double film theory. For a given single phase, the heat and mass transfer coefficients were combined with the Chilton - Colburn analogy. This procedure has been conducted in order to reduce the system variable number.

The Resolution Method and the Operating Conditions: The system equations may be divided into two subgroups [8]. The first group where several nonlinear algebraic equations are added together with the conditions of equilibrium at the interface and the definitions of mass and energy flux. This sub-system is solved by the method of Newton-Raphson:

For Liquid phase $\frac{dL}{dz} = \sum_{j=1}^{NC} \dot{N}_x^l \, 2\pi R_i$

Conservation of mass $\frac{d\dot{l}_j}{dz} = \dot{N}_{ji}^l \, 2\pi R_i$

Conservation of Energy $d\left(\dot{L}\dot{E}^l\right) + q_w \, dA_w = \sum_{j=1}^{NC} \dot{N}_{jx}^l \overline{H_l} \, dA_i + \dot{h}_x^l \, dA_i (T_l - T_i)$

For Liquid-vapor Interface $\frac{dL}{dz} == \sum_{j=1}^{NC} \dot{N}_x^g \, 2\pi R_i$

Conservation of mass $\frac{d\dot{l}_j}{dz} = \sum_{j=1}^{NC} \dot{N}_x^g \, 2\pi R_i$

Conservation of Energy $d\left(\dot{L}\dot{E}^l\right) + q_w \, dA_w = \sum_{j=1}^{NC} \dot{N}_{jx}^g \overline{H_g} \, dA_i + \dot{h}_x^g \, dA_i (T_i - T_g)$

For the Whole differential Element $\frac{dL}{dz} = \frac{d\dot{G}}{dz}$

Conservation of mass $\frac{d\dot{l}_j}{dz} = \frac{dg_j}{dz}$

Conservation of Energy $d\left(\dot{L}\dot{E}^l\right) + q_w \, dA_w = d\left(\dot{G}\dot{E}^g\right)$

Equilibrium Relation $y_{ji} = K_{ji} x_j$

Summation Relations $\sum_{j=1}^{NC} y_{ji} = 1 \quad and \; \sum_{j=1}^{NC} x_{ji} = 1$

Transfer Flux Expression $\dot{N}_{jx}^l = \dot{k}_x^l \left(\frac{\dot{l}_j}{L} - x_{ji}\right) + \; x_{ji} \sum_{j=1}^{NC} \dot{N}_j^l$

The second group which contains the differential equations and their resolution provides the gradients for the other end of the element dz. For these equations, a 4th Order Runge-Kutta method has been used, where NC represents le component number:

$$\frac{dL}{dz} = \sum_{j=1}^{NC} \dot{N}_x^g \, 2\pi R_i$$

$$\frac{dL}{dz} = \sum_{j=1}^{NC} \dot{N}_x^g \, 2\pi R_i$$

$$\frac{dG}{dz} = -\sum_{j=1}^{NC} \dot{N}_j^g \, 2\pi R_i$$

$$\frac{dg_j}{dz} = -\dot{N}_j^g \, 2\pi R_i$$

$$\dot{L} \, Cp_m^i dT^l + \sum_{j=1}^{NC} \overline{H_j^l} \, d\dot{l}_j + q_w \, dA_w - \left[\sum_{j=1}^{NC} \dot{N}_{jx} \, \overline{H}_{ji}^l - \lambda \frac{\delta T}{\delta x}\right] dA_i = 0$$

For these sections, the calculations start from the top of the column and work towards the bottom. This sequence has been chosen because all the conditions needed for starting the program calculations are known and specified with finite value at the top of the column. This study has been conducted with the assumption of constant values of heat and mass transfer coefficients from literature geometric shapes. All of physical and chemical depend on composition and temperature.

Data of entry and exit conditions have been taken to fulfill the mass and energy balance around the column are needed to solve the system equations. So the conditions and the values at the top of the column are primordial to start the calculations procedure. These calculations are developed with the aim of obtaining the composition at the bottom of the column and should be verified at the end of calculations.

For each finite element dz, given the entry data and assumptions for constant heat and mass transfer coefficients, the method of Newton-Raphson was used to determine the interfacial conditions as well as the flux density across that interface. These results are essential for the method of Runge-Kutta-Merson to give the estimated values at the exit of this finite element dz. Then, the calculation program proceeds to the next finite element z+dz and continues to reach the desired conditions.

The condtions retained for the mixture n Hexane (A) and Toulene (B):

Feed: L_F=0.0110 (moles/s), x_F=0.3 in n Hexane, T_F= 359.8(K)-Boiling point

Distillate: G_s =0.0617(moles/s), y_s=0.5 in n Hexane, T_{gs}= 366.6(K)-Dew point

Residual: L_s=0.00490(moles/s), x_s=0.05 in n Hexane, T_{ls}= 377.6(K)-Boiling point

Column diameter: 0.058 (m) and zero vapour flow at the bottom

RESULTS AND DISCUSSION

Effect of the Incident Energy Q_w: Figure 3 shows the effect of incident energy q_w on the axial profiles of concentration for the case of constant coefficient of heat and mass transfer. These coefficients were calculated by the Chilton - Colburn analogy and recorded the dew point temperature. Curves numerated from 0 to 9 on the graph where the isobaric equilibrium curve between the liquid and vapor are presented as a function of the column height in the rectification mode. In these curves, the composition x_s corresponding to the nonzero flow at the bottom of the column were searched.

The imposed power provides the source of heat so that the volatile component n Hexane leaves the liquid mixture to the vapor phase. By changing the imposed power, the column reacts as a rectification column but the initial mixture concentration must be changed in order to satisfy the condition of the absence of gas flow at its bottom.

Only Curve 6 is obtained for an imposed power of 1429 W/m and the output results correspond to the desired function of the column. In this case, the column is in the evaporation process. It also gives an exit composition at the column bottom for an almost zero value for the vapor flow. The equilibrium composition between vapor and liquid phases that fulfill the mass and energy balance for the whole column are also shown in Figure 3.

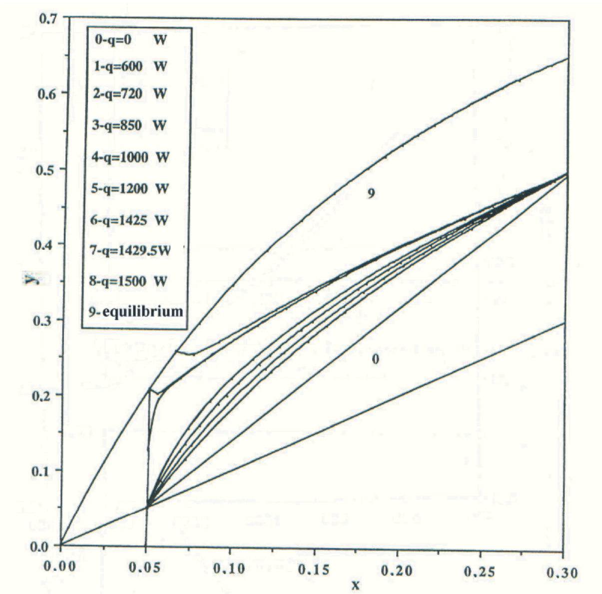

Fig. 3: Variation of the concentration as a function of the imposed power which satisfies the conditions at the bottom of the column with a constant transfer parameters as: k_x^l= 1.93 (moles/m^2 s), h_x^l= 1300 (W/m^2 K) – Chilton - Colburn analogy, k_y^g=0.2417(moles/m^2 s), h_y^g=33.76 (W/m^2 K) Chilton - Colburn analogy

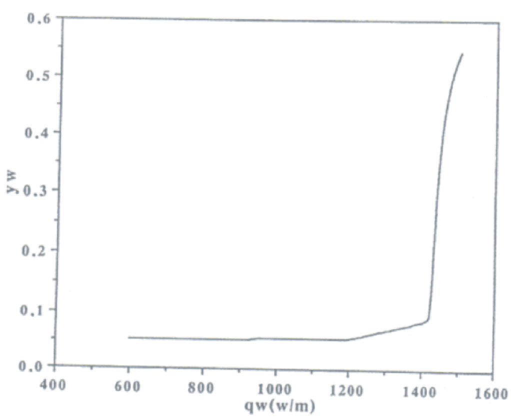

Fig. 4: Variation of the vapor composition produced at the bottom of the column in function of the imposed power

Passing this equilibrium point, further heat supply could lead the column to an excess of feeding. In this case, the evaporation occurs in a rapid manner and as a result, no equilibrium will be achieved.

Figures 4 and 5 show the evolution of the composition and the flow at the bottom of the column (exit) as a function of the imposed power of the same conditions of heat and mass transfer coefficients.

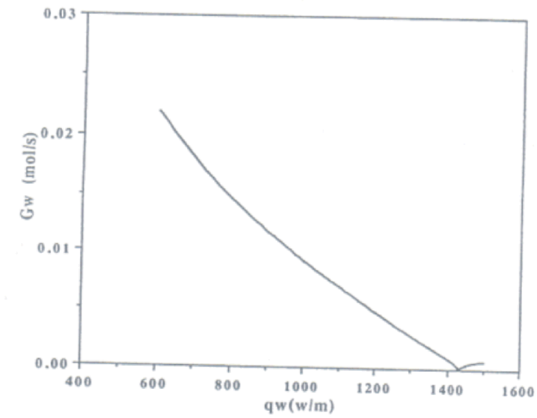

Fig. 5: Variation of the vapor flow produced at the bottom of the column in function of the imposed power

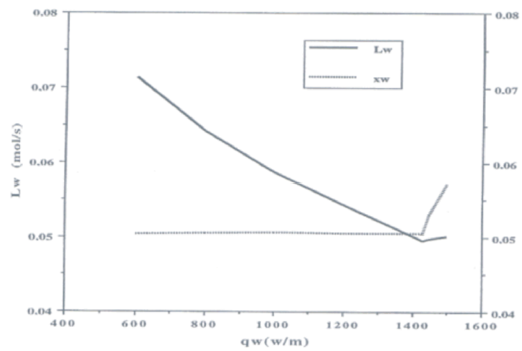

Fig. 6: Variation of the residue flow and composition in function of the imposed power

It could be noticed that the desired composition and vapor flow depends on the applied power as evaporation process on the volatile component from the binary mixture.

Figure 6 shows the non-significant changes in concentration. Non significant effect on the residual flow and column height is shown in Figure 6.

With the same imposed power applied as shown in Figure 3, the composition variations and the desired zero vapor flow in the bottom of column in function of the imposed power can be found. This figure shows high sensible variations with respect to the imposed power with the maximum peak value at 1429 W/m. It is noted that the input power is a primordial parameter for this type of apparatus in order to satisfy the thermal and hydrodynamic reliable conditions.

Incident of liquid and mass transfer coefficients: In order to study the effect of the increasing of fluid resistance on the liquid heat and mass transfer, coefficient on the behavior of the model while keeping the conditions in the vapor phase are unchanged.

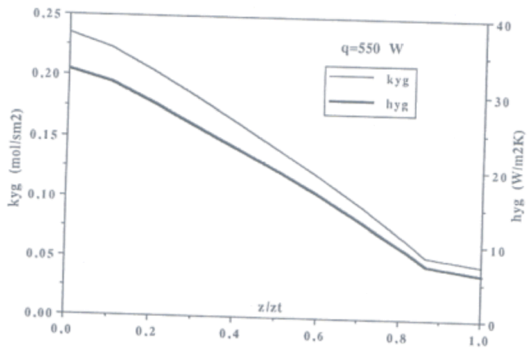

Fig. 7: Variation of heat and mass transfer coefficient in liquid phase in function of columns height

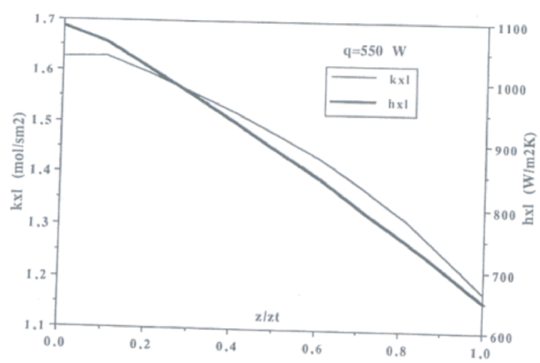

Fig. 8: Variation of heat and mass transfer coefficient in vapor phase in function of columns height

By changing the value of the imposed power, it is noted that the same variation as before but this effect was clearly noticed with respect to Y_w and G_w at the bottom of the column.

Figure 7 and 8 which have been established for a specified power of 550 W/m as a function of the non-dimensional axe Z/Z_T. Regarding these variations, an important modification in physical and chemical properties and flow conditions should be considered. The effects of these conditions as a function of the imposed power that fulfill the same bottom column conditions.

CONCLUSION

By modeling the falling film evaporation with the specific case, the vapor flow at the column bottom is null. The most important parameter noticed is the contribution of the global resistance to transfer. It could be noted that higher dependency on the liquid phase parameters on the column height, the phases compositions and the flux density. This model provides the ability to change the operating mode from rectification mode to evaporation mode. The imposed power transmitted through the wall, then transferred by the liquid film to the interface is the principal factor for the exchange between phases. Although this study has been conducted with a constant energetic flux per unit height, it permits to obtain the optimum energy as a function under consideration (composition and/or flow at the bottom of the column) and also the local internal energy needs. In addition, the definition of the applied technique for producing and adopting energy are necessary to achieve the optimal performance.

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